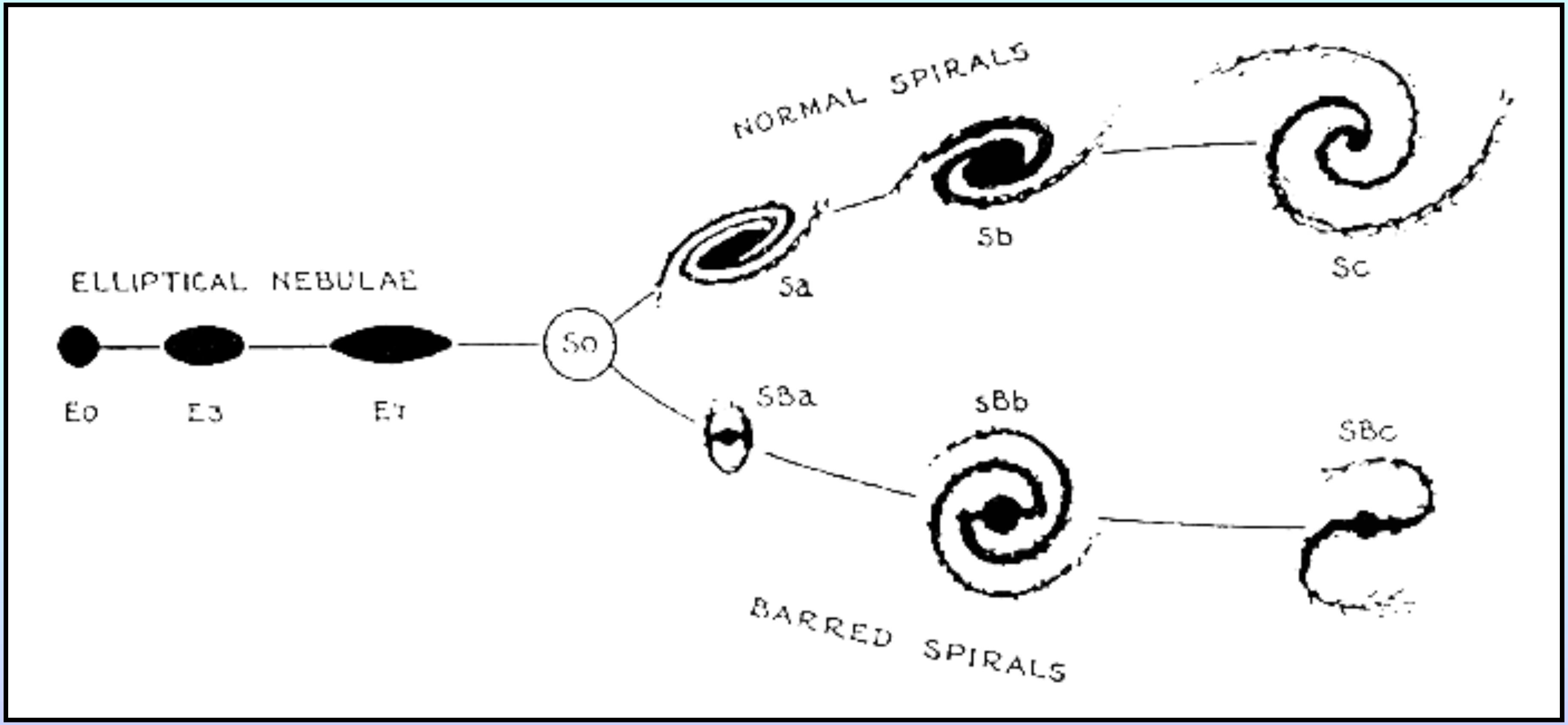
Stellar Populations

Walter Baade divided galaxies into two components:

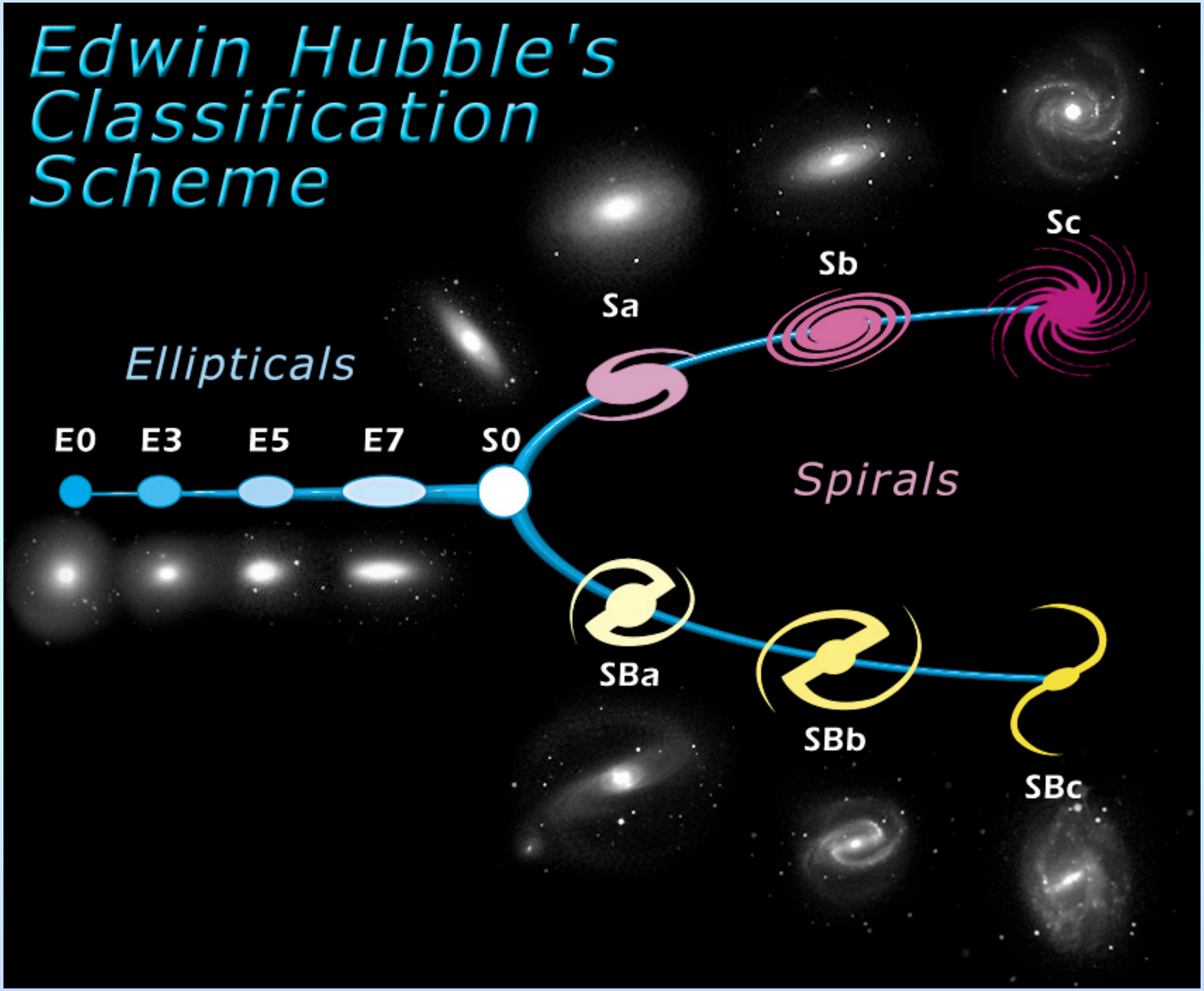
- Population I: objects closely associated with spiral arms – luminous, young hot stars (O and B), Cepheid variables, dust lanes, H II regions, open clusters, metal-rich
- Population II: objects found in spheroidal components of galaxies (bulge of spiral galaxies, ellipticals) – older, redder stars (red giants), metal-poor
- Note several different fundamental properties affect observed color:
  - Metallicity (metal poor stars are bluer than metal rich stars)
  - Age (younger stars are bluer)
  - Dust (makes stars redder)

Galaxy Classifications

There are many ways to classify galaxies. (After all, it's like butterfly collecting.) There are about a half-dozen qualitative classification schemes and a similar number of quantitative schemes. The most famous is the "tuning fork" sequence first proposed by Hubble in the 1930s.

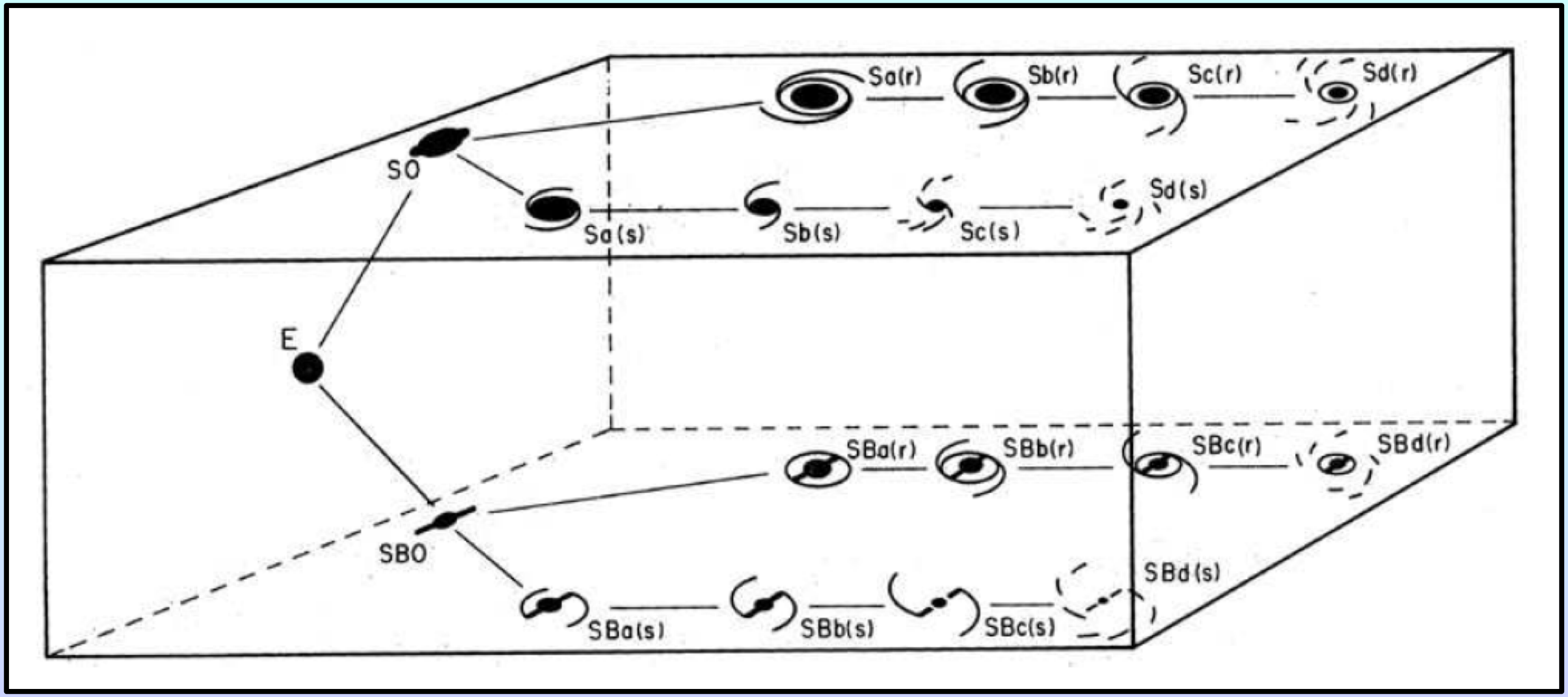


The Hubble Tuning-Fork Diagram



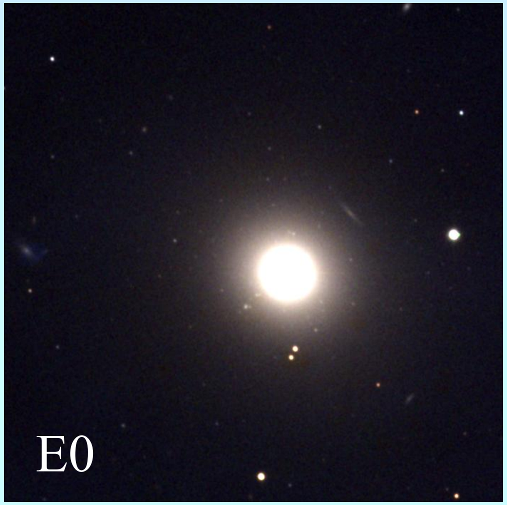
Extensions to the Hubble Sequence

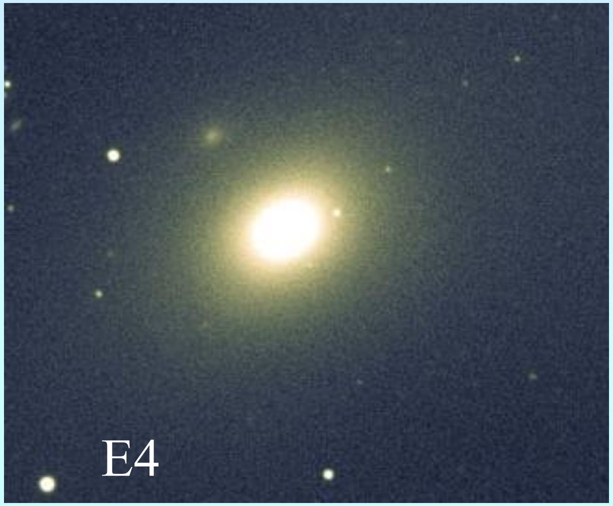
- Sandage introduced:
  - Notation SA for unbarred galaxy (to match SB for barred)
  - Notation SAB for intermediate, weakly barred systems
  - Symbols (r) and (s) to indicate systems with and without rings

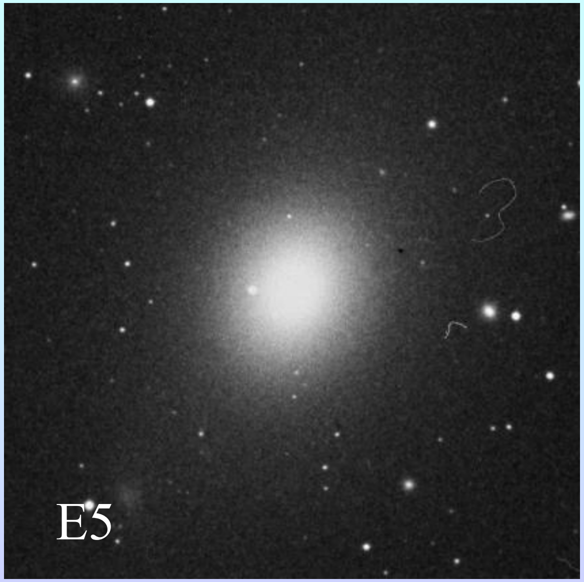


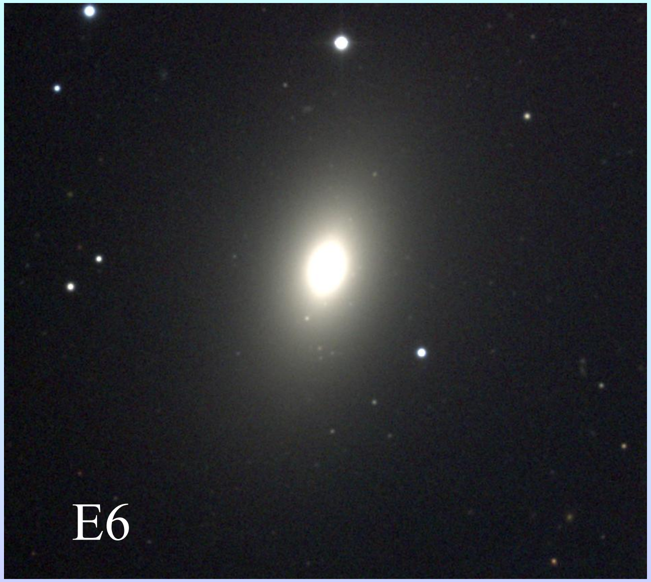
Elliptical Galaxies

Elliptical galaxies are classified En, with $n = 10\,(1 - b/a)$



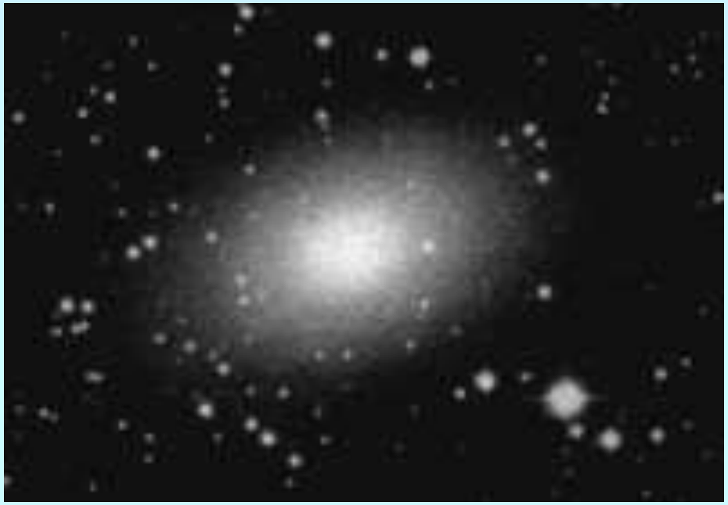
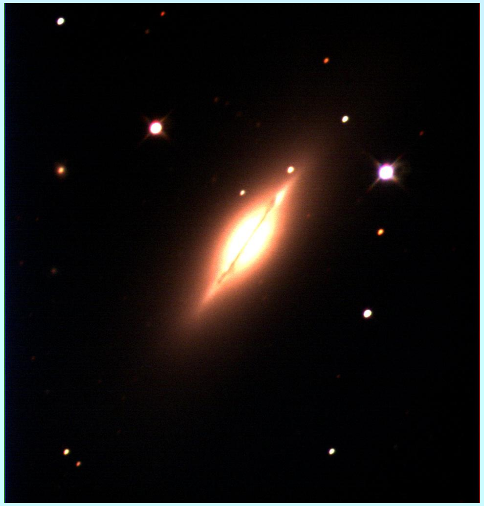
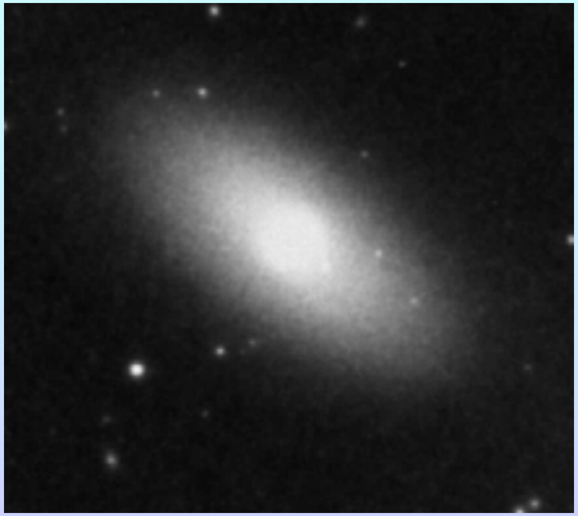






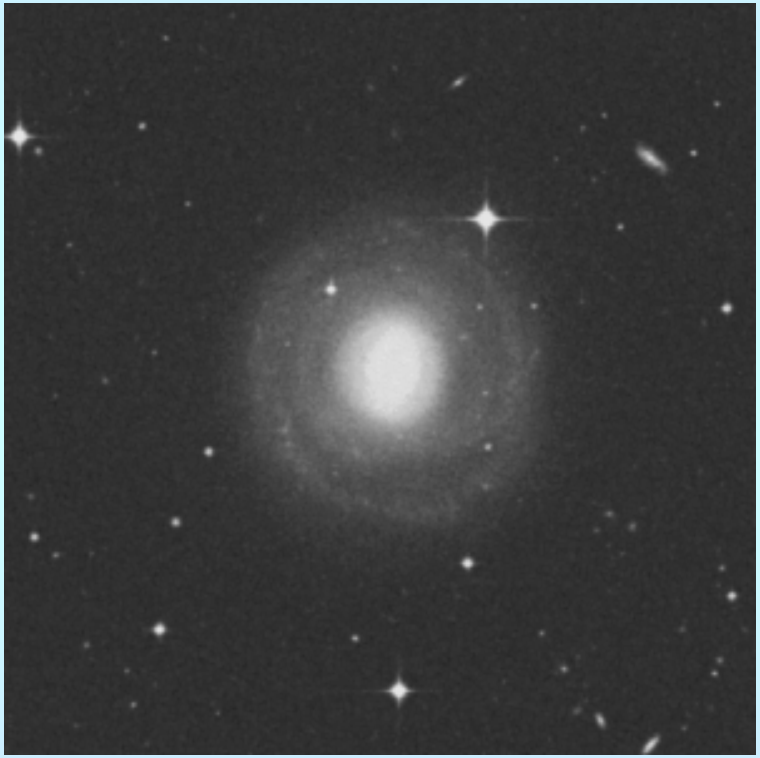
Lenticular (S0 and SB0) Galaxies

S0 and SB0 galaxies are transition objects. They are disk systems, but almost exclusively Pop II, with no star formation, no spiral arms, and very little cold gas or dust.

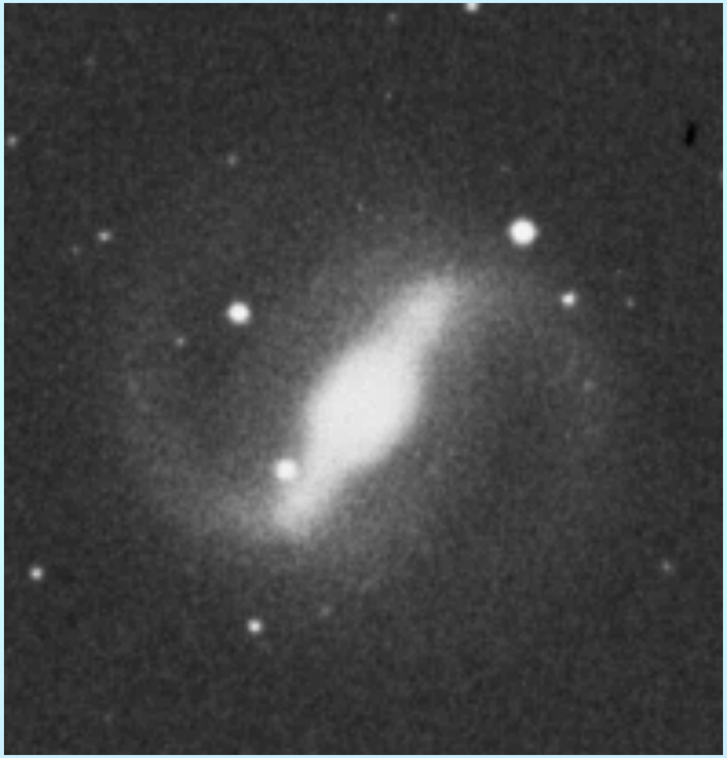
Sa and SBa Galaxies

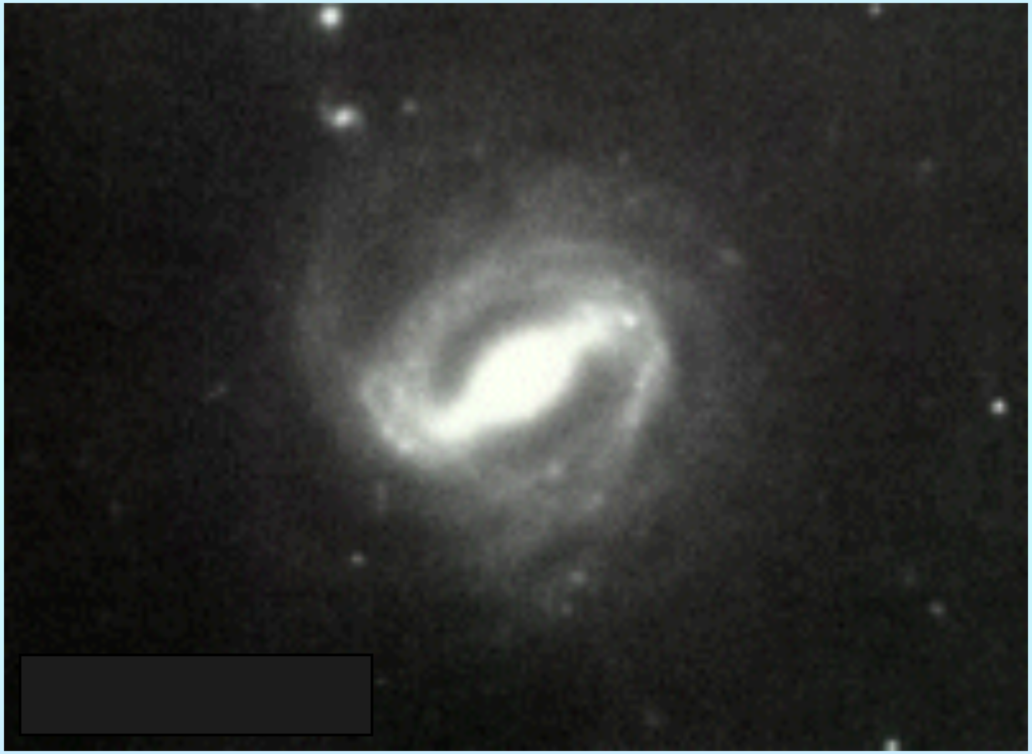
Sa and SBa galaxies have a large (dominant) Pop II bulge, and a very smooth disk with only a trace of spiral arms.



Sa and SBa Galaxies

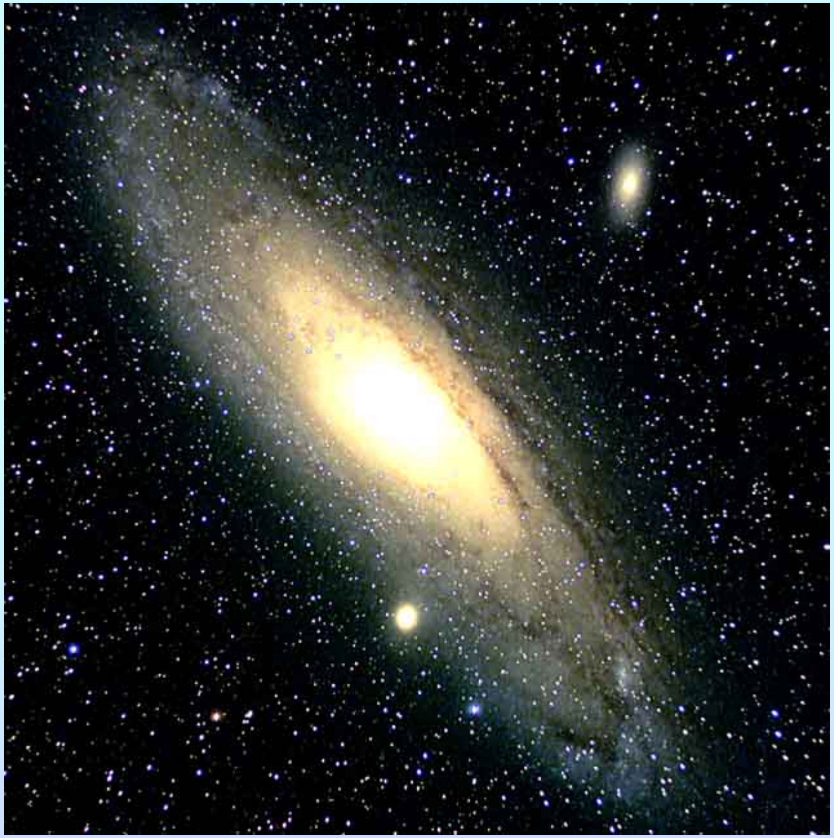
Sa and SBa galaxies have a large (dominant) Pop II bulge, and a very smooth disk with only a trace of spiral arms.





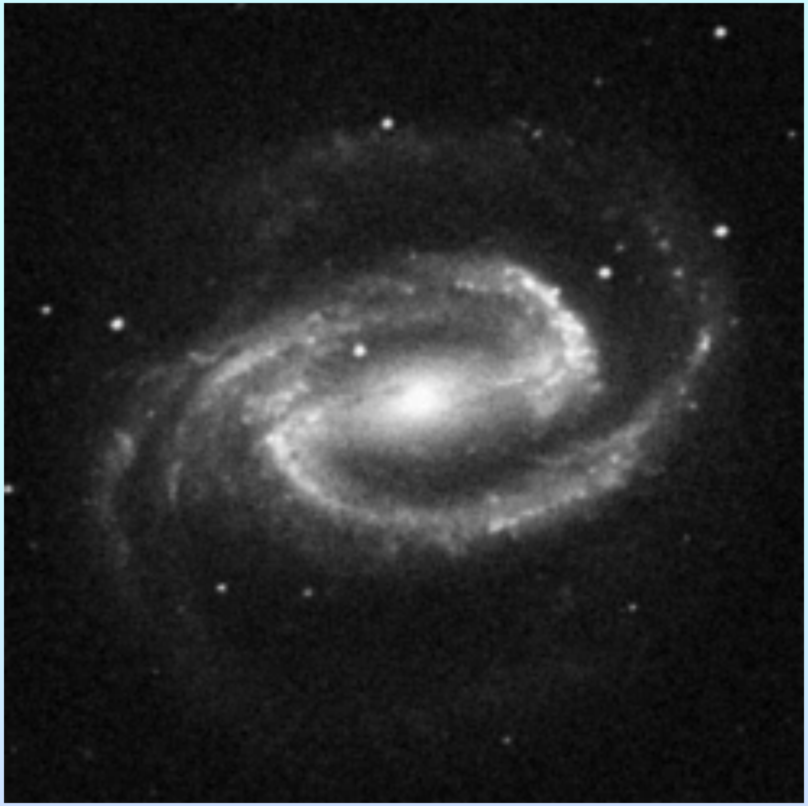
Sb and SBb Galaxies

In Sb and SBb galaxies, the bulge and disk components are comparable. Spiral structure is becoming visible in the disk, and some individual H II regions can be seen.



Sb and SBb Galaxies

In Sb and SBb galaxies, the bulge and disk components are comparable. Spiral structure is becoming visible in the disk, and some individual H II regions can be seen.

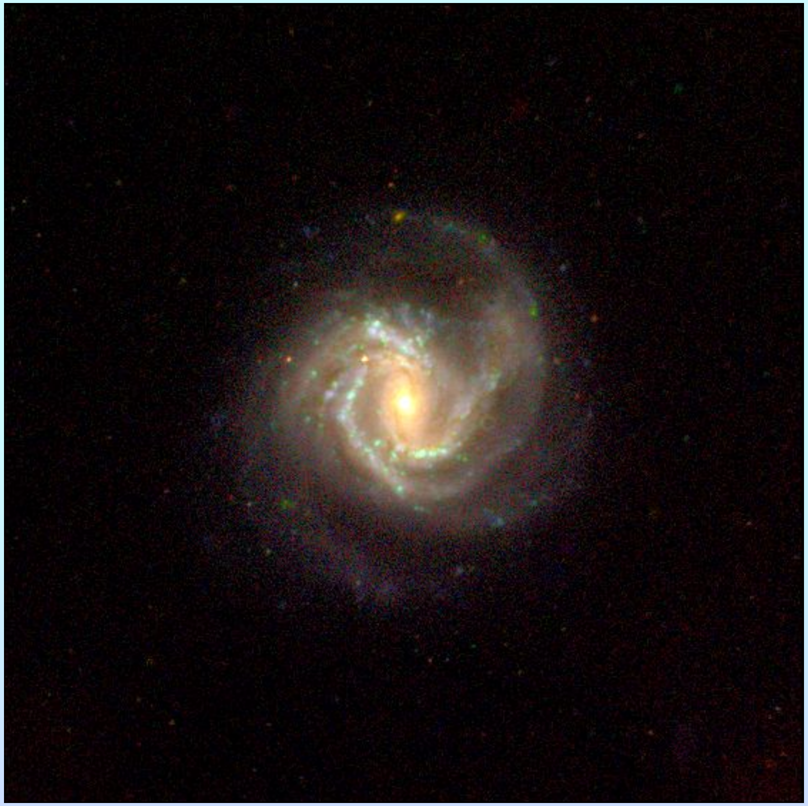


Sc and SBc Galaxies

Sc and SBc galaxies have little or no bulge, but do have a prominent Population I disk with clearly defined spiral arms. These arms appear knotty due to their many H II regions.

Sc and SBc Galaxies

Sc and SBc galaxies have little or no bulge, but do have a prominent Population I disk with clearly defined spiral arms. These arms appear knotty due to their many H II regions.

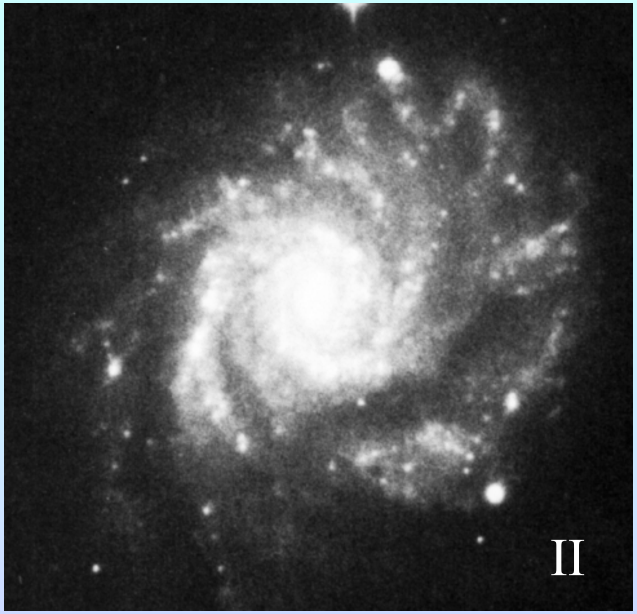


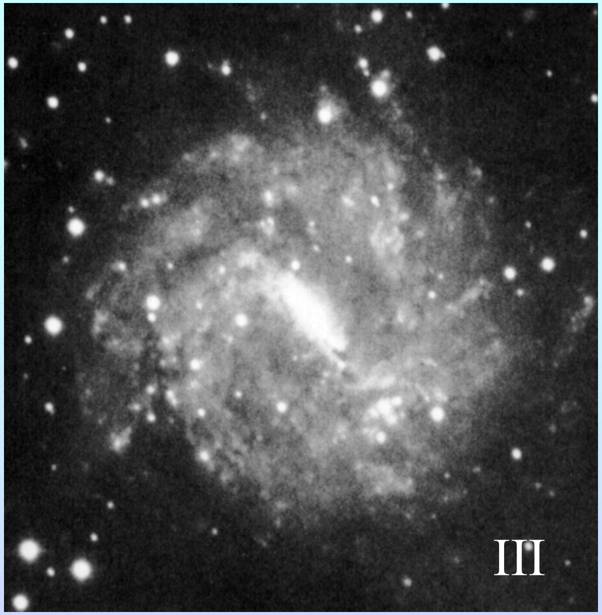
Extensions to the Hubble Sequence

De Vaucouleurs (1960) added three new classes: Sd, Sm, and Im. (The Large Magellanic Cloud is an SBm; the Small Magellanic Cloud is an Im galaxy.)

Extensions to the Hubble Sequence

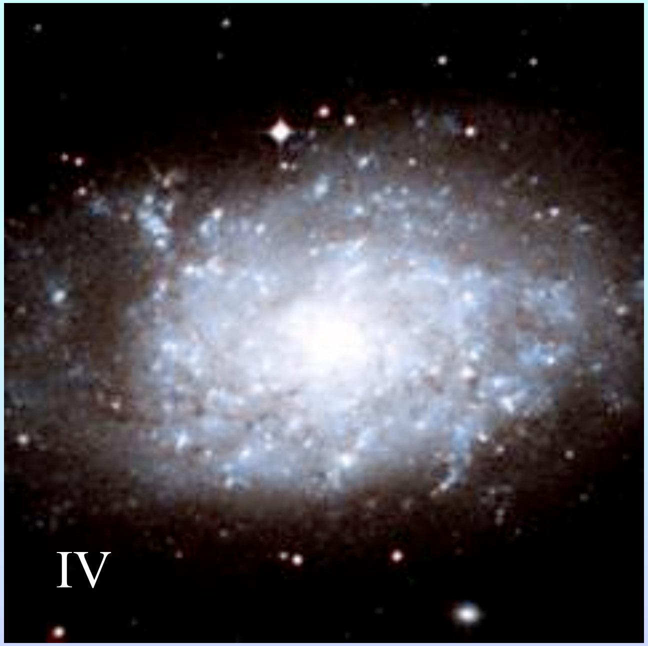
- Van den Bergh (1960) added luminosity classes based on arm quality/length. (This is the DDO System.) Like stellar luminosity classifications, these go from V (dwarf) to I (supergiant), with
  - I: strong, well-defined arms, most luminous galaxies, $M_B < -21$
  - V: chaotic, small arms, least luminous spirals, usually Sd-Im, $M_B = > -17$

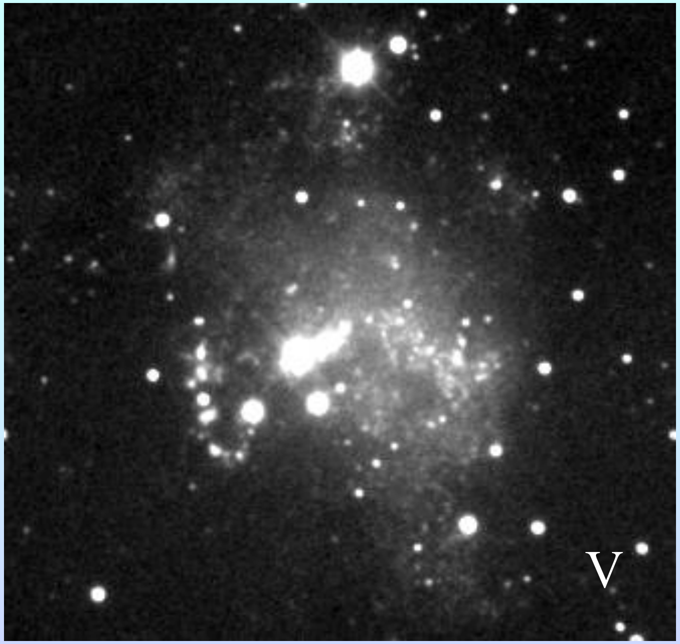




Extensions to the Hubble Sequence

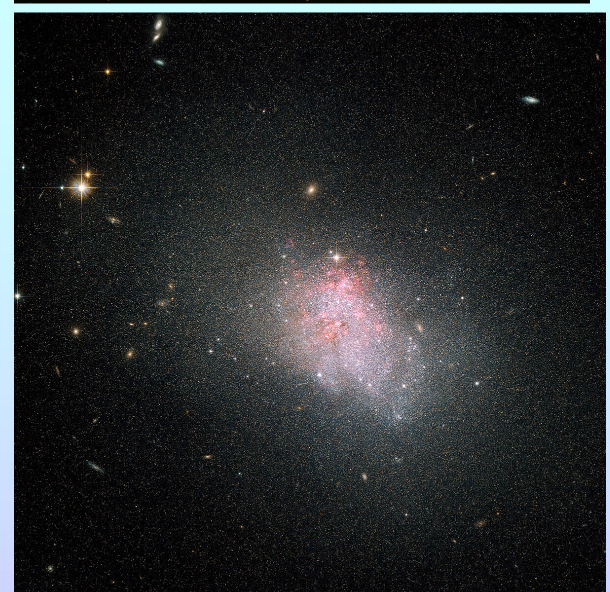
- Van den Bergh (1960) added luminosity classes based on arm quality/length. (This is the DDO System). Like stellar luminosity classifications, these go from V (dwarf) to I (supergiant), with
  - I: strong, well-defined arms, most luminous galaxies, $M_B < -21$
  - V: chaotic, small arms, least luminous spirals, usually Sd-Im, $M_B = > -17$





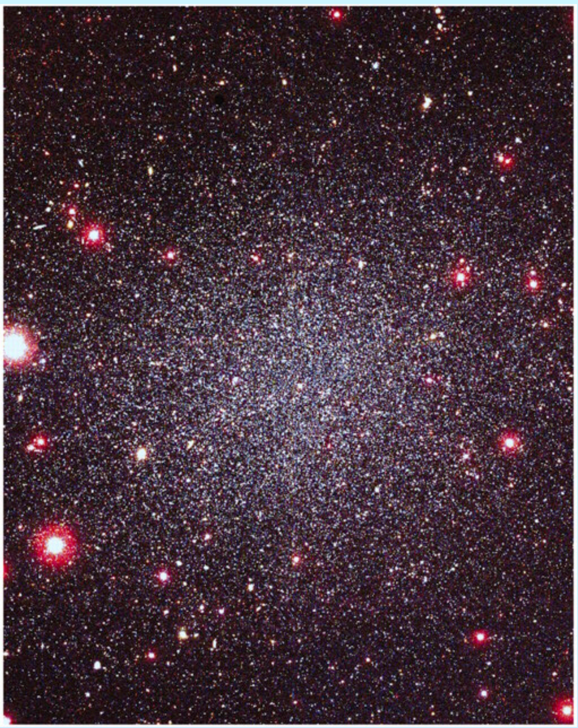
Galaxies Missing from the Hubble Sequence

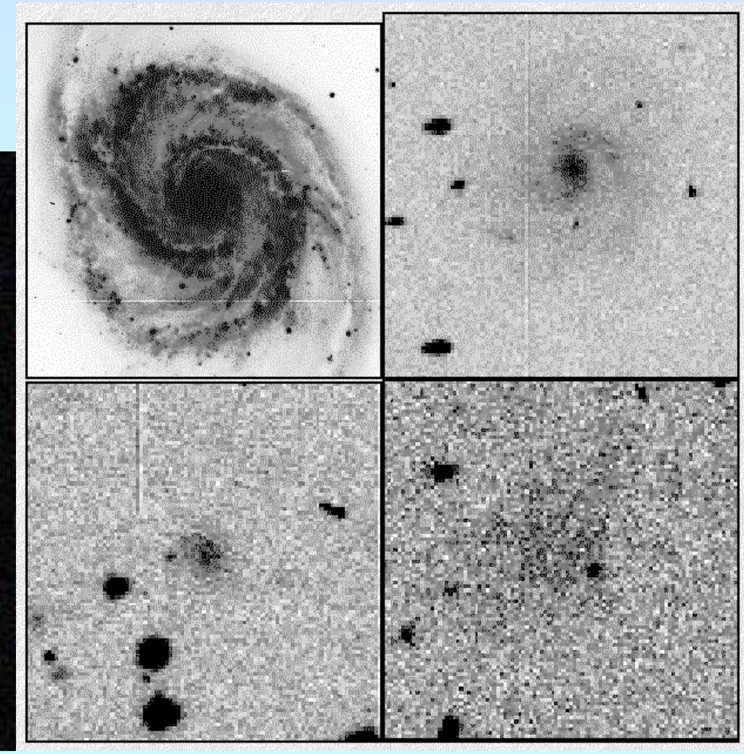
- Dwarf galaxies
  - Ellipticals
  - Spheroidals
  - Irregulars

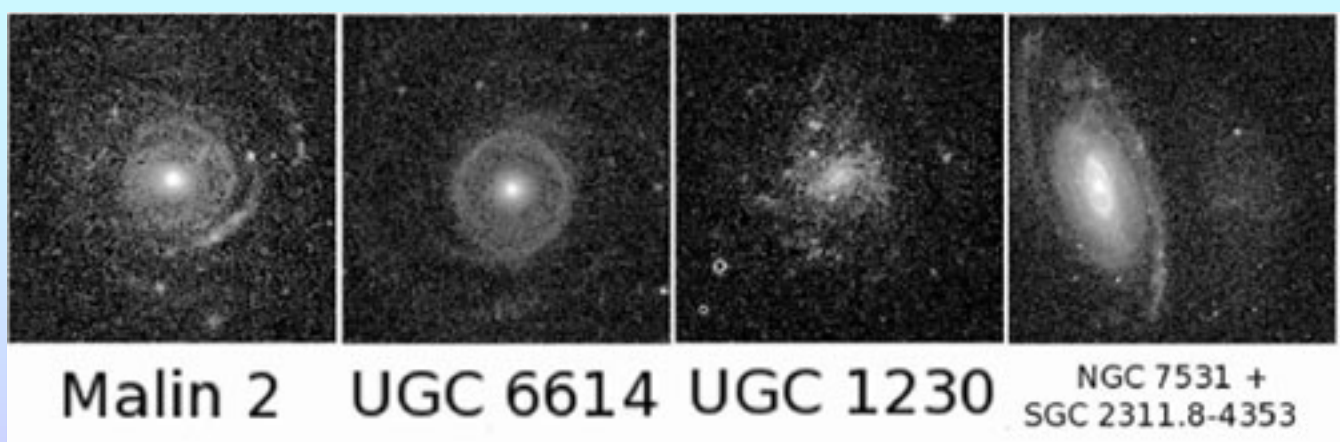


Galaxies Missing from the Hubble Sequence

- Low Surface Brightness galaxies







Galaxies Missing from the Hubble Sequence

- Peculiar (usually interacting) galaxies
  - Many cataloged by Arp (1966)

Galaxy Catalogs

- In late 1700's, Messier made a catalog of 109 nebulae so that comet hunters wouldn't mistake them for comets!
  - ~ 40 of these were galaxies, e.g., M31, M51, M101.
  - Most are gaseous nebulae within the Milky Way, e.g., M42, the Ring Nebula, etc.
  - Some are globular clusters (M3, M13); some are open clusters (M45 = the Pleides).
- New General Catalogue (Dreyer 1888)
  - Like the Messier catalog, these are non-stellar objects
  - Based on lists by Herschel (5079 objects), plus a bunch more for a total of 7840 objects
  - ~ 50% are galaxies

Galaxy Catalogs

- Index Catalogue (IC) – (Dreyer 1895, 1898)
  - Additions to the NGC, 6900 more objects
- Shapley-Ames Catalog (Harvard 1932)
  - Bright galaxies, $m_{pg} < 13.2$
  - Whole-sky coverage, fairly homogenous
  - 1246 galaxies, all in the NGC or IC catalogs
  - Revised by Sandage & Tamman in 1981 (RSA)
- Uppsala General Catalog (UGC --Nilson 1973)
  - Based on Palomar Observatory Sky Survey (POSS)
  - Size limited, $d > 1$ arcmin
  - Since Mt. Palomar is outside San Diego, objects all have $\delta > -18^\circ$
  - 13000 objects

Galaxy Catalogs

- Reference Catalog of Bright Galaxies (de Vaucouleurs)
    - RC1: 2599 galaxies (1964)
    - RC2: 4364 galaxies (1976)
    - RC3: 23,064 galaxies (1991)
- The 2nd and 3rd Reference Catalogue classify galaxies using "T"-types ranging from –5 to 10:
    - E = –5, E/S0 = –3, S0 = –2, S0/a = 0
    - Sa = 1, Sab=2, Sb=3, Sbc = 4, Scd =6
    - Sdm=8, Im=10
- No distinction made between barred and non-barred galaxies

Galaxy Catalogs

- ESO (European Southern Observatory) Catalog
  - Similar to UGC in southern sky, $\delta < 30°$
  - 18000 objects
- Morphological Catalog of Galaxies (MCG) by Vorontsov-Vel'yaminov et al.)
  - Based on POSS plates
  - 29000 objects, $-2° > \delta > -18°$
  - Classification scheme that is far too complicated for ordinary mortals
- Zwicky catalog
  - Based on photographic material
  - 6 catalogs of galaxies with $m < 15.1$

Galaxy Atlases

- Hubble Atlas (Sandage 1961)
  - Presents plates used by Hubble in his developing classification system plus an explanation of the system
- Nearby Galaxies Catalog and Atlas (Tully 1988)
  - V < 3000 km/s
- Arp Atlas of Peculiar Galaxies
- Atlas of Galaxies Useful for measuring the Cosmological Distance Scale (Sandage & Bedke 1988)
- Carnegie Atlas (Sandage & Bedke 1994) – Images of galaxies in the Revised Shapley Ames Catalog

Catalogs and Atlases of Galaxies

- More recent galaxy surveys – APM survey, CfA Redshift Survey, 2dF redshift survey, Sloan Digital Sky Survey (SDSS), and many, many others. Objects named via their coordinates, i.e., J193423+44682
- The NASA/IPAC Extragalactic Database (NED) is a good source of information on galaxies, plus has many galaxy catalogs on-line:

http://ned.ipac.caltech.edu/

Galaxy Luminosity Functions

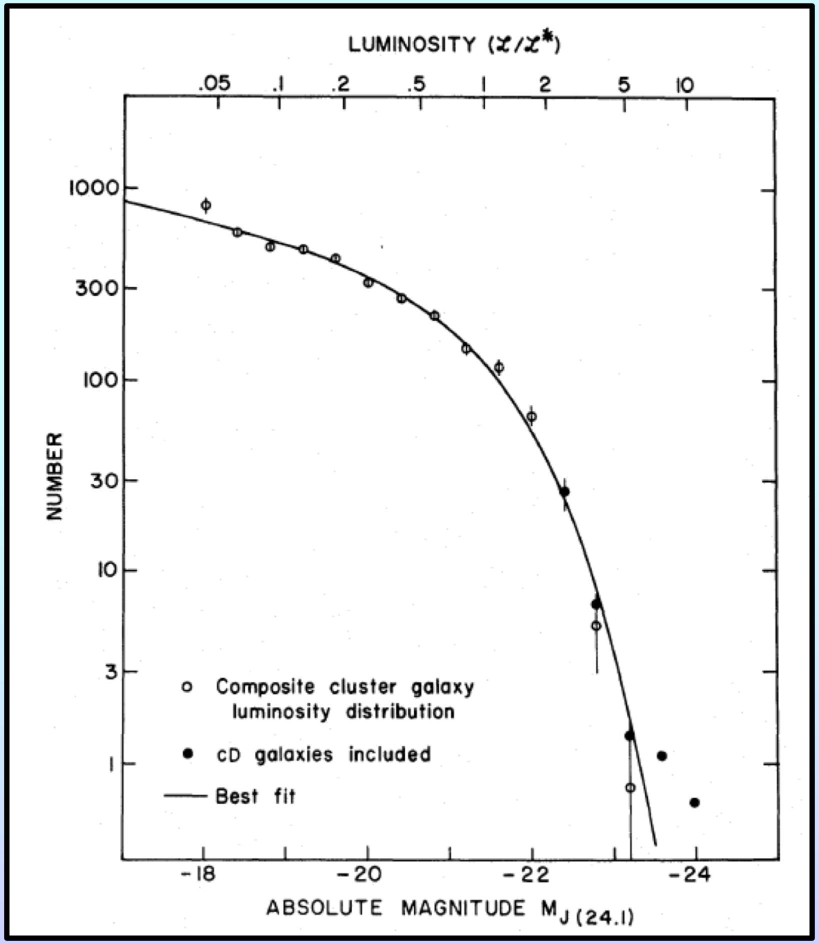
Galaxies have a range of luminosities, from absolute magnitudes of $M \sim -22$ down to $M \sim -8$ (or fainter)! One describes the relative number of galaxies of a given brightness as a luminosity function. The most-used parameterization of this function is given in Schechter (1976)

$$\varphi(L)dL = \varphi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \frac{dL}{L^*}$$

Note the 3 parameters: the bright-end "knee", L^*, the faint-end slope, α, and the normalization, φ^*. In terms of magnitudes, this is

$$\varphi(M)dM = 0.921\,\varphi^* X^{\alpha+1} e^{-X} dM \quad \text{where}$$

$$X = 10^{0.4(M^* - M)}$$



Galaxy Luminosity Functions

Typical values for the Schechter parameters are $\alpha \sim -1.2$, $M^* = -21$ and $\varphi^* = 0.002$ galaxies/Mpc^3.

Note: the total number of galaxies in the universe is simply the integral of the Schechter function from infinite to zero luminosity. If we let $t = L/L^*$, then

$$N = \int_0^\infty \varphi(L) dL = \varphi^* \int_0^\infty \left(\frac{L}{L^*}\right)^\alpha e^{-L/L^*} \left(\frac{dL}{L^*}\right) = \varphi^* L^* \int_0^\infty t^\alpha e^{-t} dt$$

This is called an Euler integral, and, for $\alpha \geq -1$, it has the solution

$$N = \varphi^* L^* \int_0^\infty t^\alpha e^{-t} dt = \varphi^* L^* \Gamma(\alpha + 1)$$

For $\alpha < -1$, the argument of the gamma function is less than zero, implying an infinite number of galaxies.

Galaxy Luminosity Functions

Note: even if the Schechter function says there are an infinite number of galaxies/Mpc^3, this is not necessarily a problem. Note that the total luminosity contained in these galaxies is

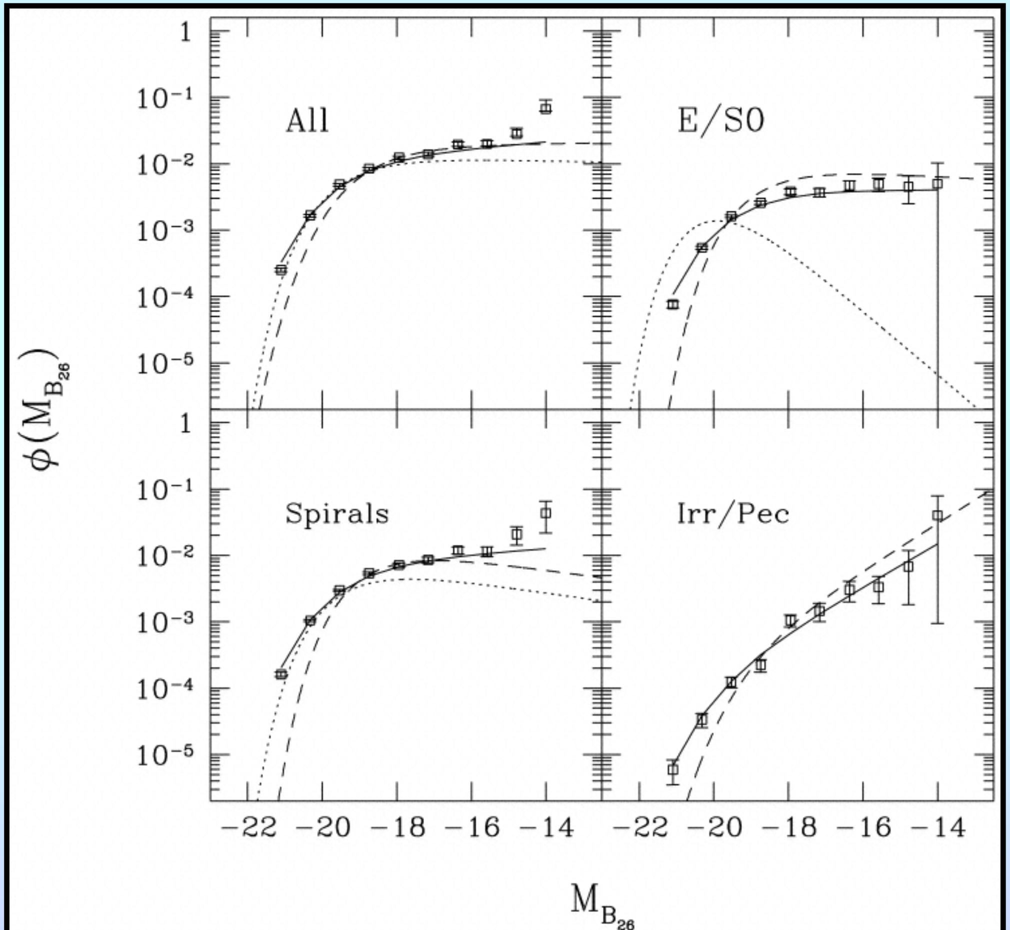
$$L(\text{tot}) = \int_0^\infty L \cdot \varphi(L) dL = \varphi^* \int_0^\infty L \cdot \left(\frac{L}{L^*}\right)^\alpha e^{-L/L^*} \left(\frac{dL}{L^*}\right) = \varphi^* L^* \, \Gamma(\alpha + 2)$$

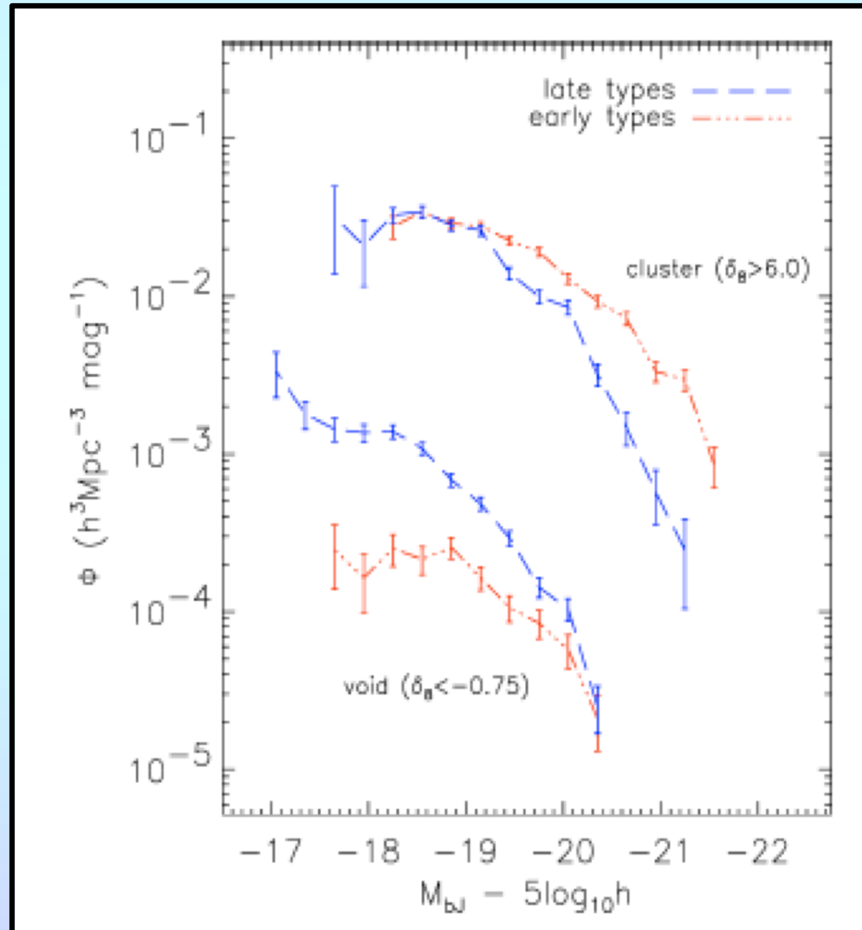
So, as long as $\alpha > -2$, the total luminosity in the universe is finite.

If, instead of counting all galaxies (i.e., to $L = 0$), you want to count down to some limiting luminosity ($L = L_{\text{faint}}$), the integral then becomes the complement of an incomplete gamma function (which is a type of confluent hypergeometric function). There are tables, expansions, and approximations for this function (see the Handbook of Mathematical Functions by Abramowitz & Stegun), but it's usually just easier to integrate the curve numerically.

Galaxy Luminosity Functions

Note: the Schechter parameters φ^*, L^*, and α and not orthogonal! Errors in one parameter affect the others! These parameters also may change as a function of galaxy type, environment, and time.





Overview of Galaxy Properties

	E	S0	Sa	Sb	Sc	Sd	Irr
Color	Red	→					Blue
Stellar Pop.	Old	Old + Intermediate		Old + Intermediate + Young		Intermediate + Young	
SFR	zero	low →		higher →			high
HI (gas)	Zero/ low	low →		modest →		high	highest
dust	Zero/ low	Higher		highest			Lower (less metals)
Dyn.	Bulge/halo dom.		Disk dominated, so rotation				

Elliptical Galaxies

- Dynamically "hot" systems, with $\sigma > v_{rot}$
- There are a number of different types of galaxies that people call "ellipticals"
  - E's (normal ellipticals)
  - cD's (massive bright galaxies at the centers of galaxy clusters)
  - dE's (dwarf ellipticals)
  - dSph's (dwarf spheroidals)

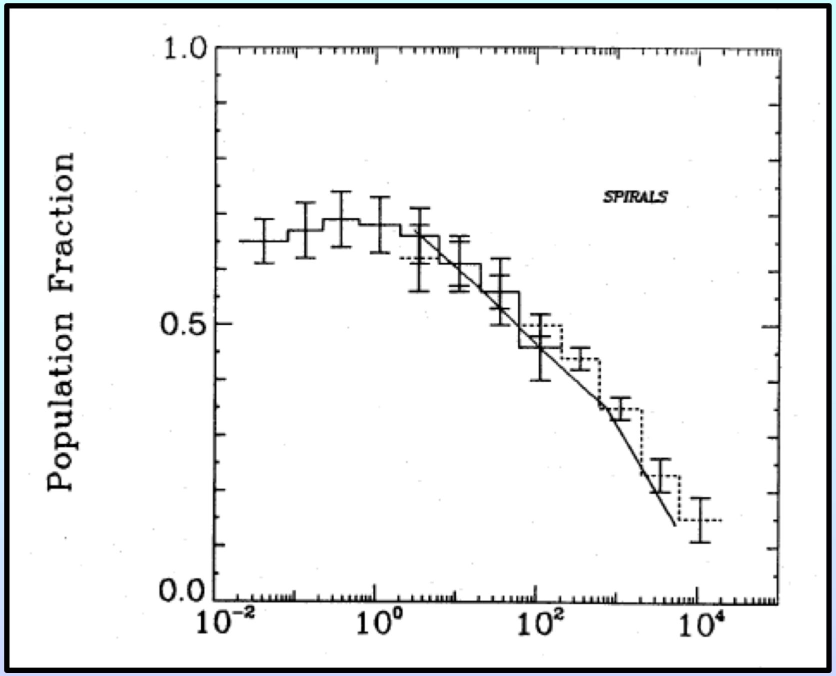
- Dwarf ellipticals are essentially scaled down versions of normal ellipticals. But cDs and dSphs are *very* different, both kinematically and structurally.

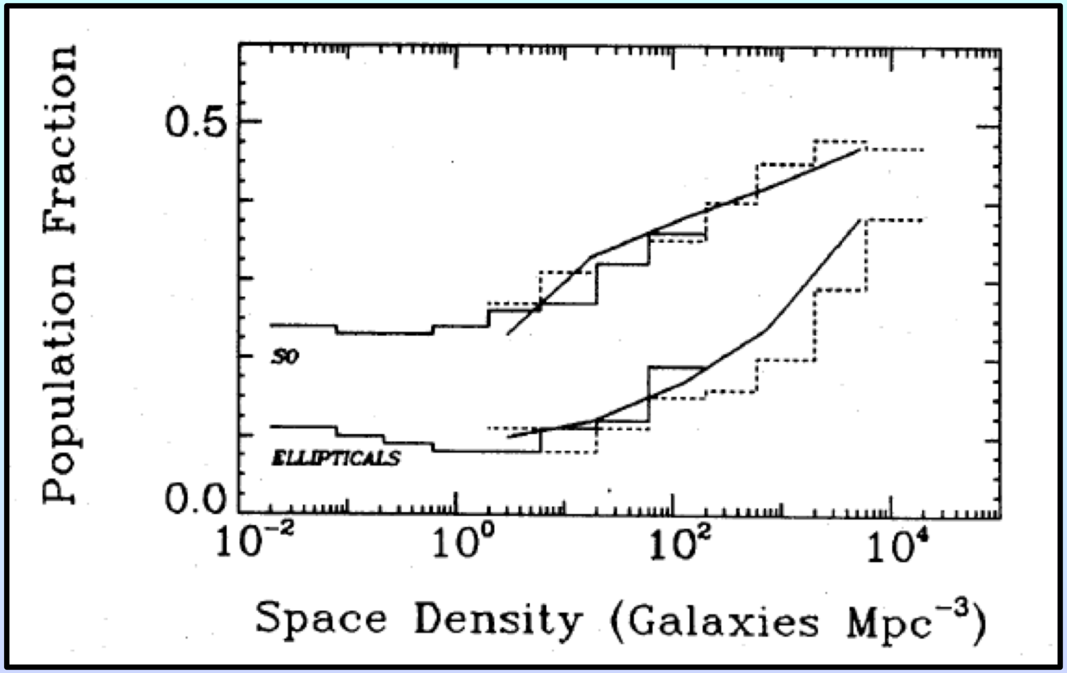
Elliptical Galaxies

- Little or no cold/warm ISM. For a typical $\sigma \sim 200$ km/s velocity dispersion.

$$\frac{1}{2} m_H v^2 \sim \frac{3}{2} kT \quad \Rightarrow \quad T \sim 10^6 \text{ degrees}$$

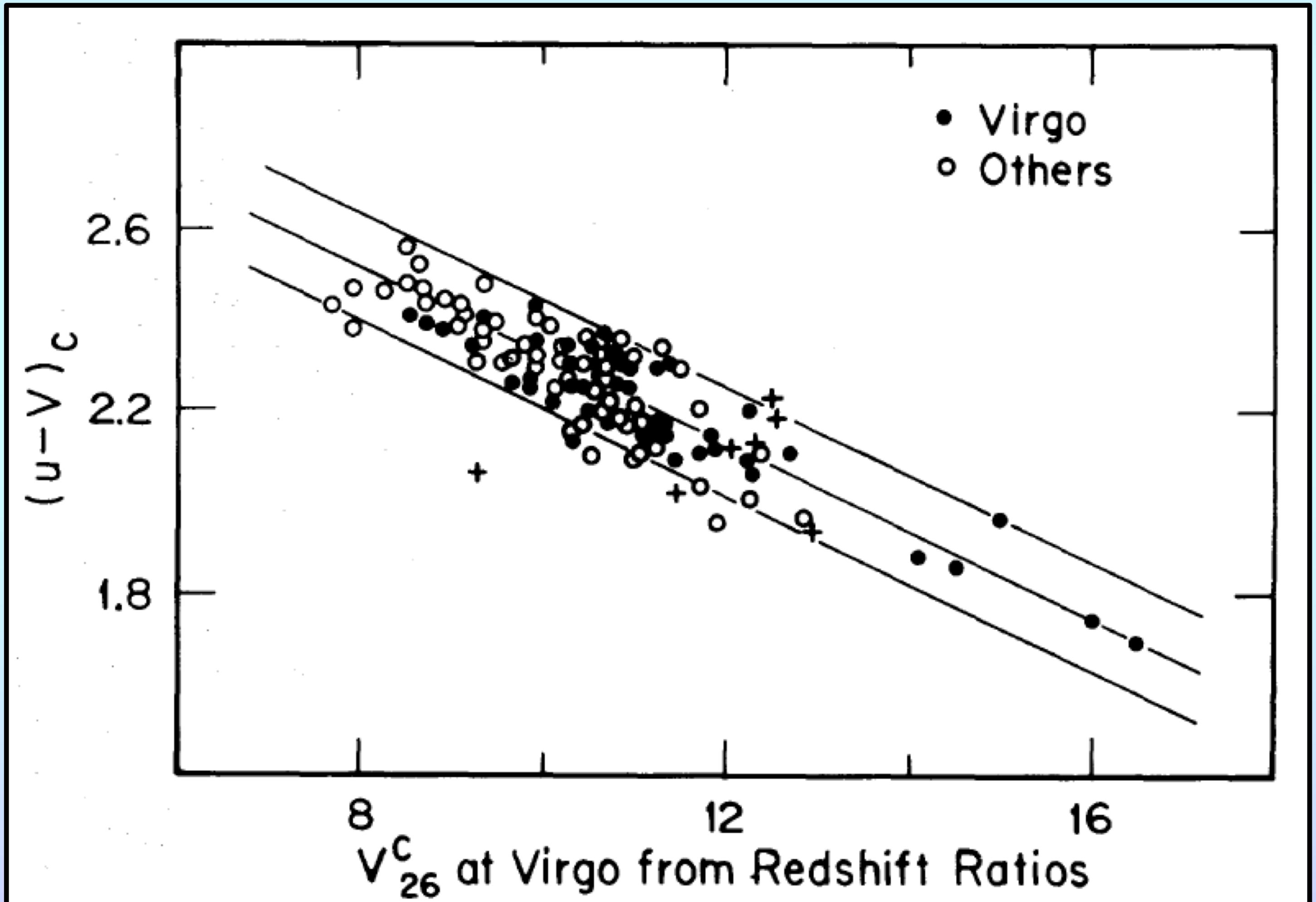
- Elliptical galaxies are preferentially found in clusters. Only ~20% of field galaxies are elliptical





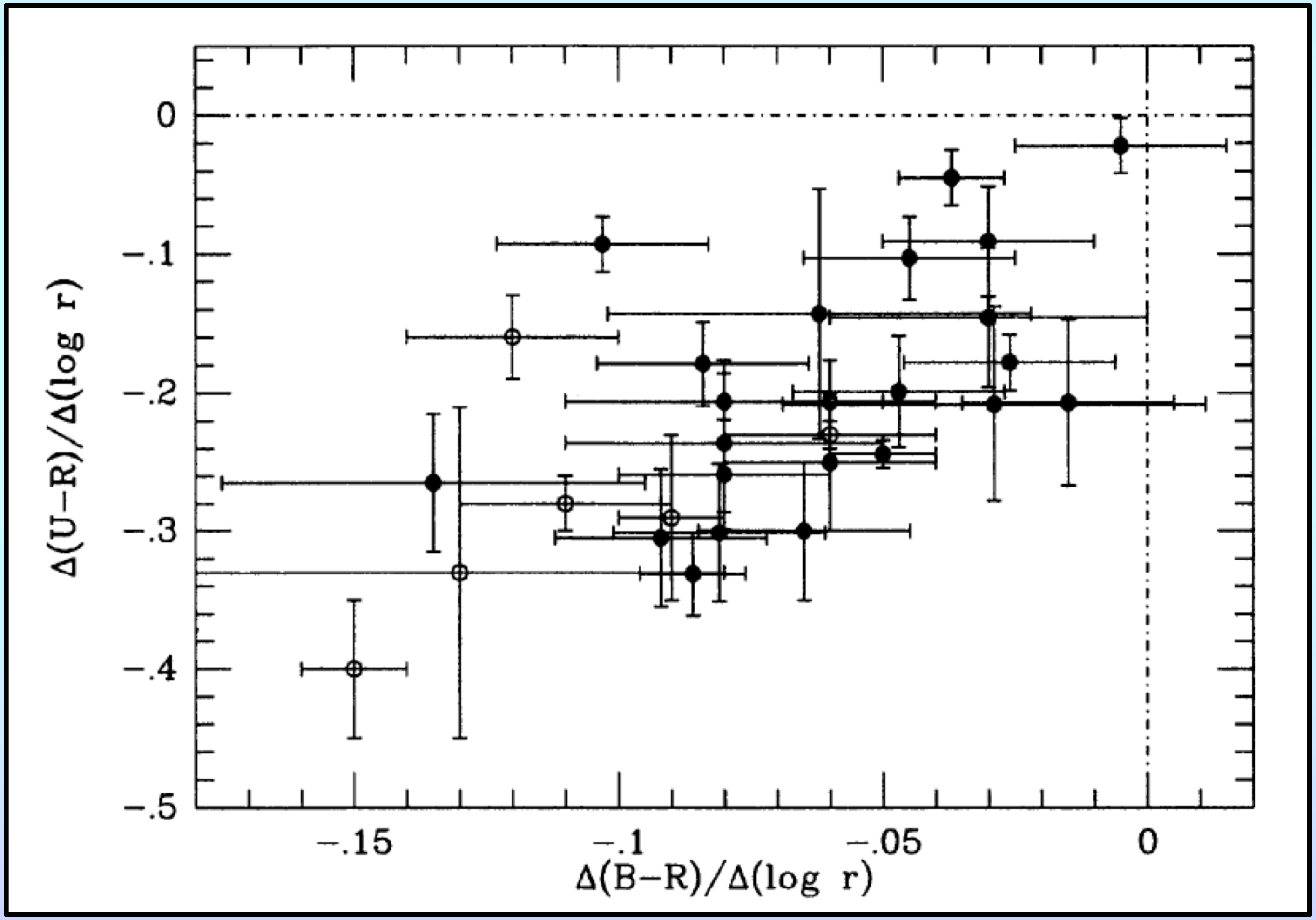
Elliptical Galaxies

- There is a color-magnitude relation for ellipticals. More luminous ellipticals are redder. This is either an age or metallicity effect (and maybe both).



Elliptical Galaxies

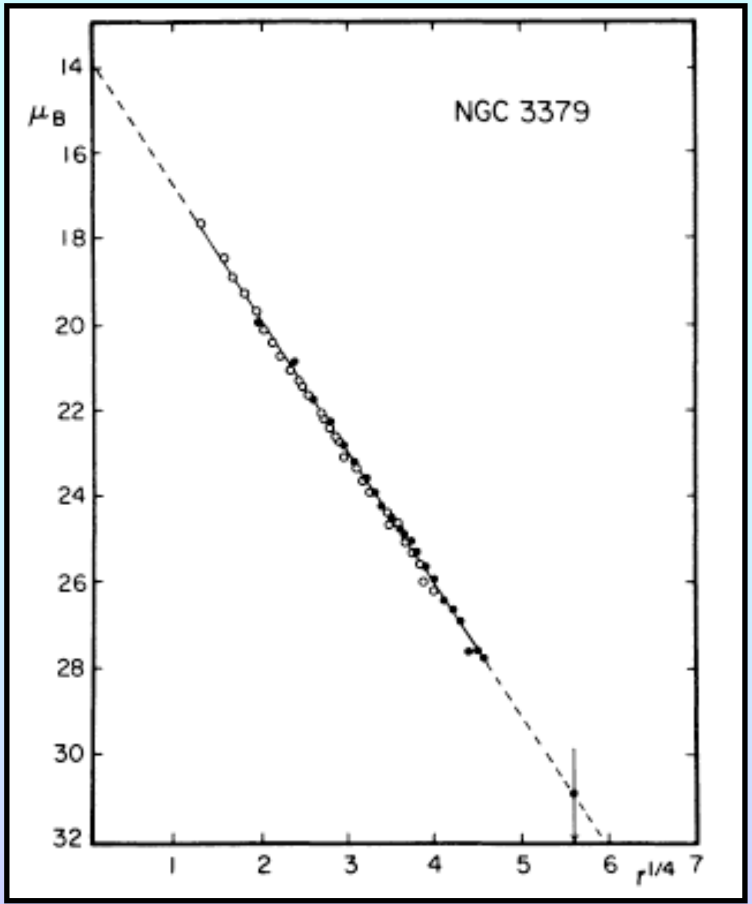
- The insides of elliptical galaxies are redder than the outsides of elliptical galaxies. (In other words, there is a color gradient.) This is probably due to metallicity (or age).



Elliptical Galaxies

- Ellipticals are the most condensed type of galaxy; the traditional "de Vaucouleur" (1948) surface brightness profile, a.k.a. the $R^{1/4}$ law, is

$$m = a + b\,R^{1/4} \quad \Rightarrow \quad \log\left(\frac{I}{I_e}\right) = -3.33071\left\{\left(\frac{R}{R_e}\right)^{1/4} - 1\right\}$$

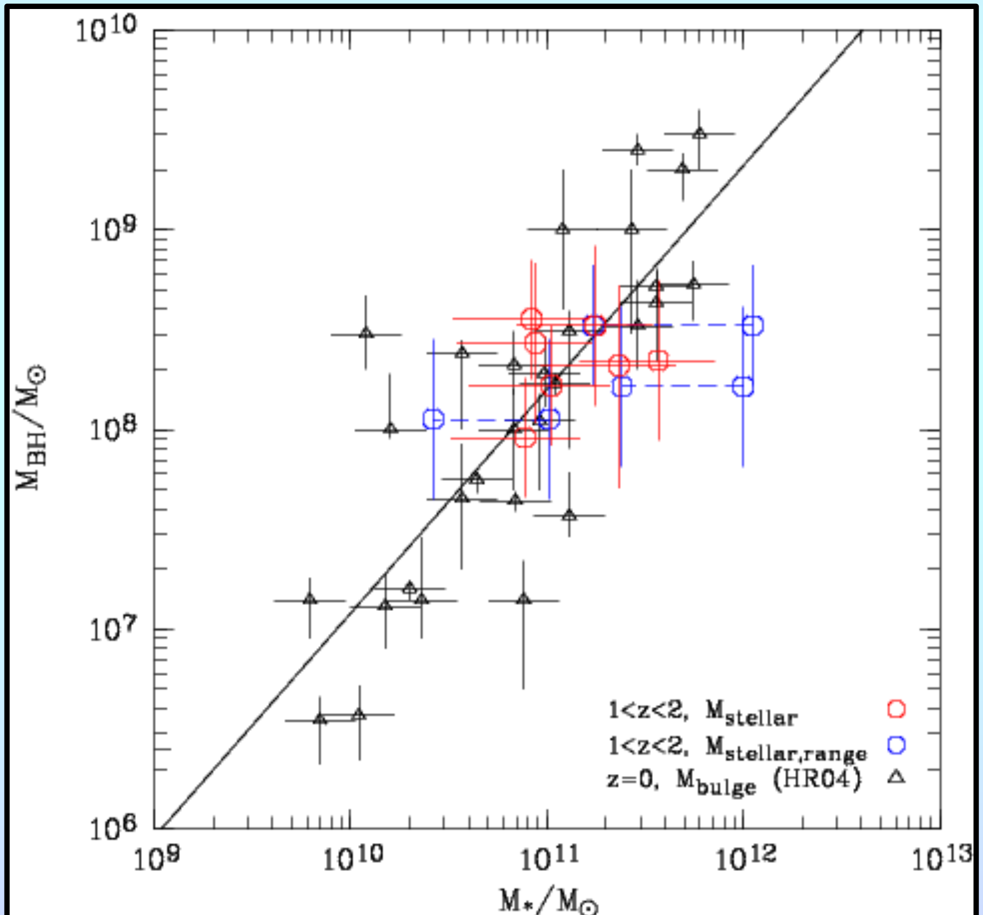


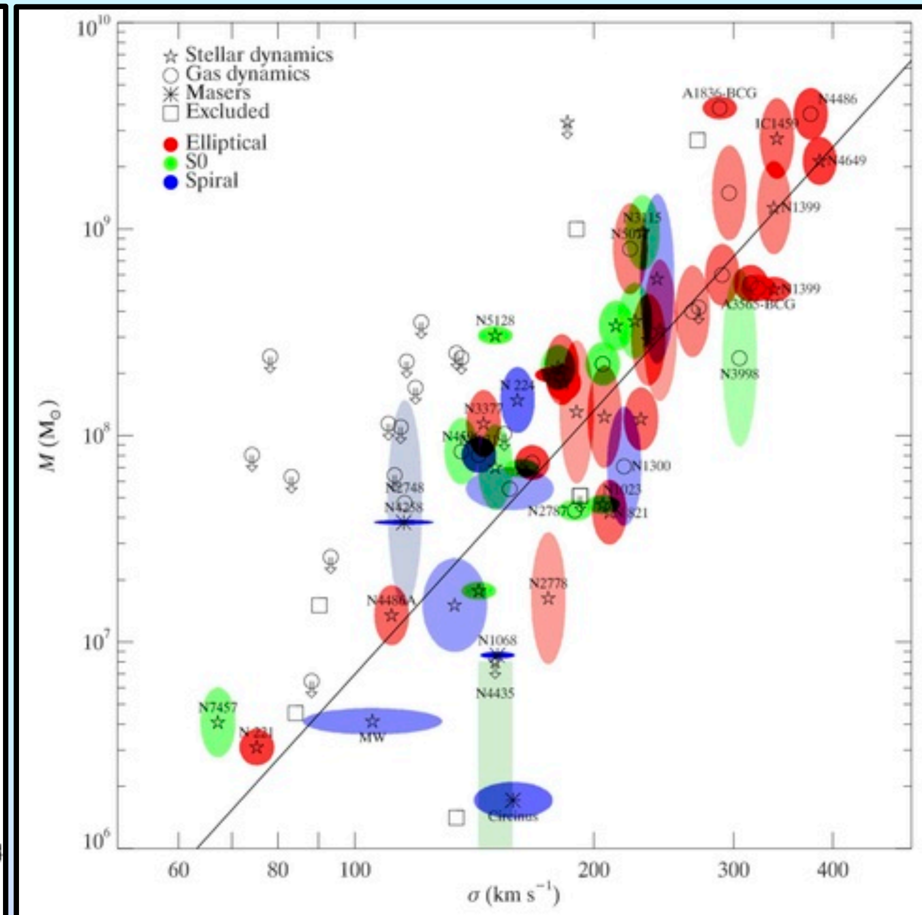
R_e is the *projected* radius that contains ½ the light and I_e is the surface brightness at R_e. (See also Young 1976).

Note: dynamically speaking, $R^{1/4}$ laws are difficult to work with. There are other laws (Hernquist laws; Jaffe laws) that are simple in 3-D, but more complicated in projected 2-D space.

Elliptical Galaxies

- The luminosity of an elliptical galaxy (or the bulge of a spiral galaxy) is related to the mass of its central black hole). The spheroidal luminosity is also related to velocity dispersion.





The Fundamental Plane

There is a relationship between the luminosity of an elliptical galaxy and its stellar velocity dispersion. Assume that all ellipticals

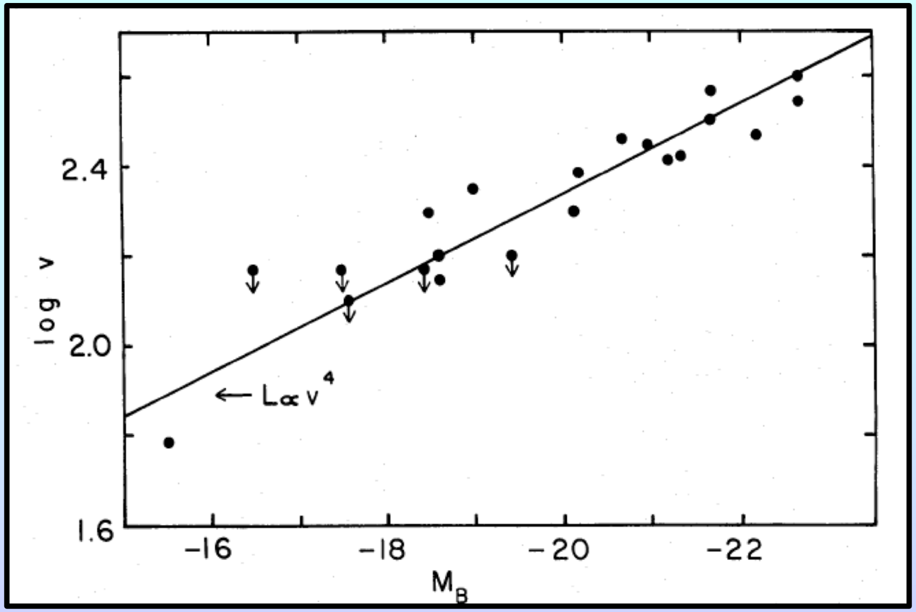
1) are in virial equilibrium: $\sigma^2 \propto M/R$
2) have the same M/L ratio: $L \propto M$
3) have the same surface brightness $I \propto L / R^2 \Rightarrow R^2 \propto L / I$

Then

$$\sigma^2 \propto \frac{M}{R} \propto \frac{L}{R} \propto \frac{L}{\sqrt{L}} \propto L^{1/2} \quad \Rightarrow \quad L \propto \sigma^4$$

This is the Faber-Jackson relation.

Note that if condition (3) is released, $L \propto \sigma^4 / I$. This is the *Fundamental Plane* for elliptical galaxies (although the coefficients are closer to 2.7 and –0.7).

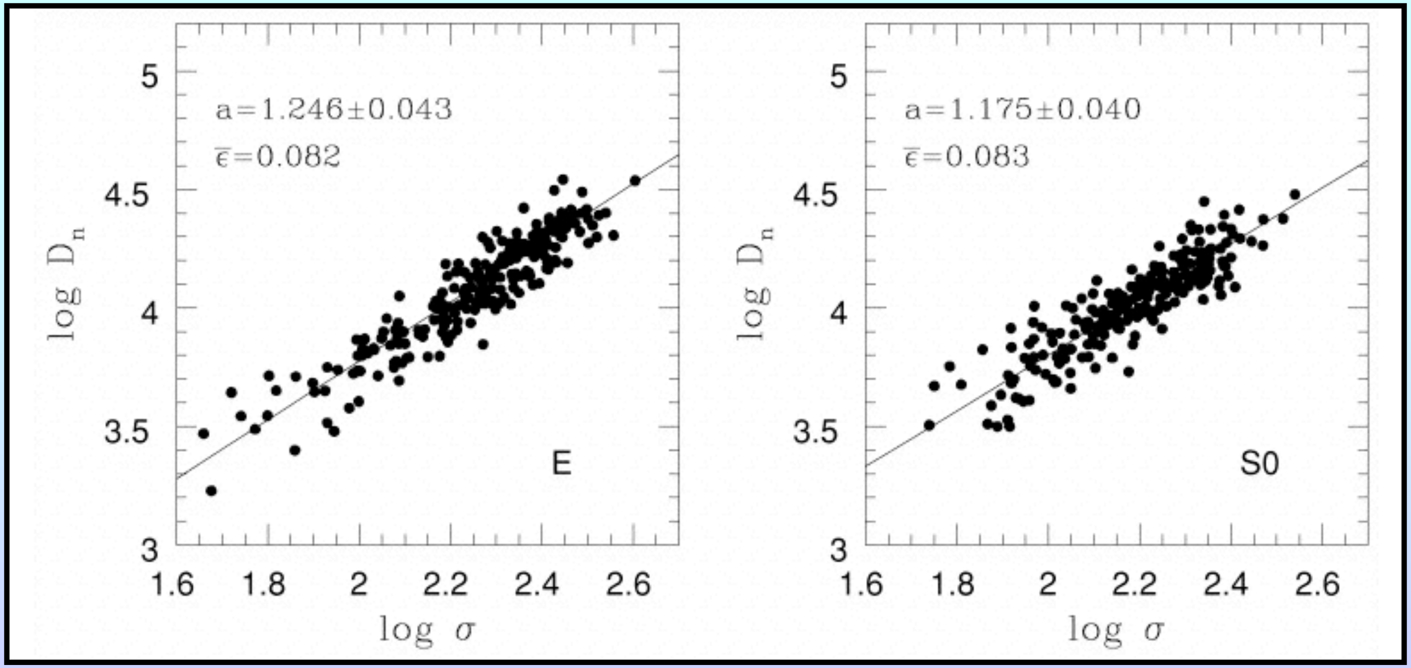


The D_n-σ Relation

Note: if one integrates the $R^{1/4}$ law (it's analytic, but sporting), then the "size" of the galaxy (defined by the average surface brightness within an aperture, defined as I) works out to be $D_n \propto R_e\, I^{\,0.8}$. But the fundamental plane implies that

$$L \propto \sigma^4 I^{-1} \quad \Rightarrow \quad I R^2 \propto \sigma^4 I^{-1} \quad \Rightarrow \quad R \propto \sigma^2 I^{-1}$$

So $D_n \propto \sigma^2\, I^{\,-0.2}$ or (since the dependence on I is small) $D_n \propto \sigma^2$. (In practice the coefficient is closer to 1.4.) This the D_n-σ relation.



The D_n-σ Relation

Note: if one integrates the $R^{1/4}$ law (it's analytic, but sporting), then the "size" of the galaxy (defined by the average surface brightness within an aperture, defined as I) works out to be $D_n \propto R_e I^{0.8}$. But the fundamental plane implies that

$$L \propto \sigma^4 I^{-1} \quad \Rightarrow \quad I R^2 \propto \sigma^4 I^{-1} \quad \Rightarrow \quad R \propto \sigma^2 I^{-1}$$

So $D_n \propto \sigma^2 I^{-0.2}$ or (since the dependence on I is small) $D_n \propto \sigma^2$. (In practice the coefficient is closer to 1.4.) This the D_n-σ relation.

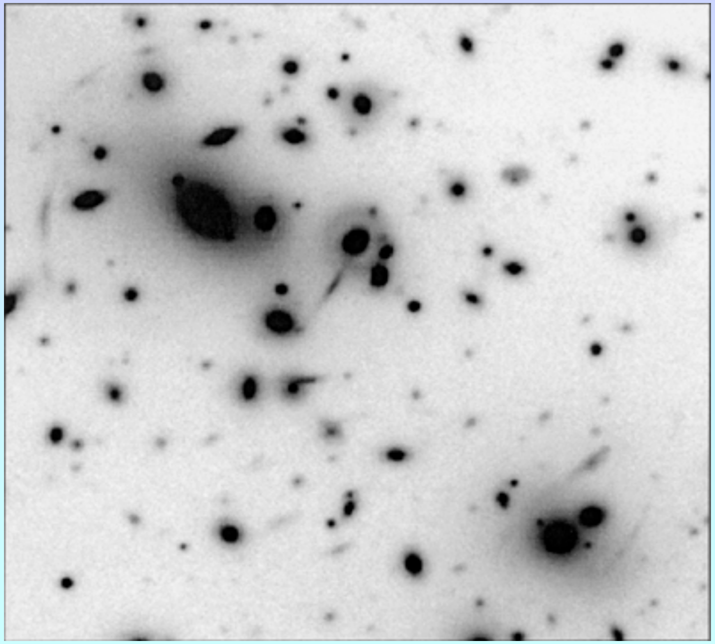
In general, many of the properties of elliptical galaxies --- luminosity, color, velocity dispersion, strength of absorption lines, etc., are correlated.

cD Galaxies

central Diffuse (cD) galaxies sit near the bottom of cluster potentials, and can thought of as "galaxies at lunch."

The surface brightness profiles of cD galaxies are often shallower than that given by the $R^{1/4}$ law, hence the "diffuse" classification.

In some cases, the envelopes of cD galaxies can be traced over most of its cluster.

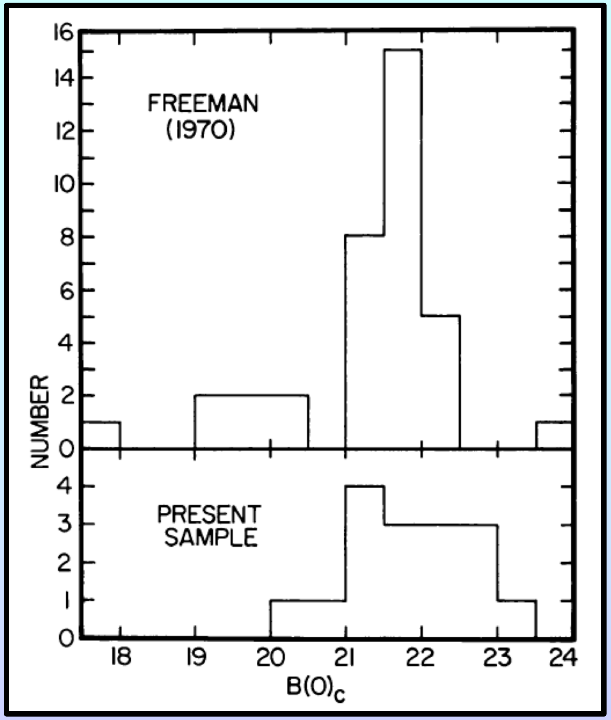


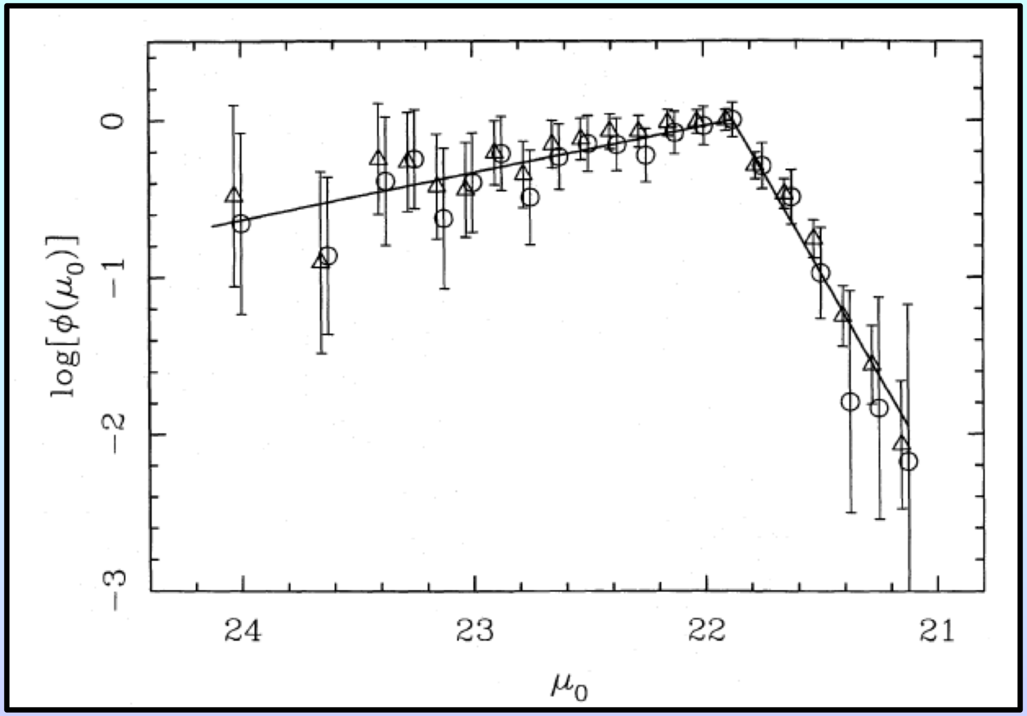
Spiral Galaxies

- About ¾ of galaxies in the field are spirals
- To a very good approximation, the surface brightness distribution of a spiral disk can be parameterized as an exponential

$$I(r) = I_0\, e^{-r/r_0}$$

- I_0, central surface brightness, was at one time thought to be roughly constant for all spirals, but this is a selection effect.





Spiral Galaxies

- About ¾ of galaxies in the field are spirals
- To a very good approximation, the surface brightness distribution of a spiral disk can be parameterized as an exponential

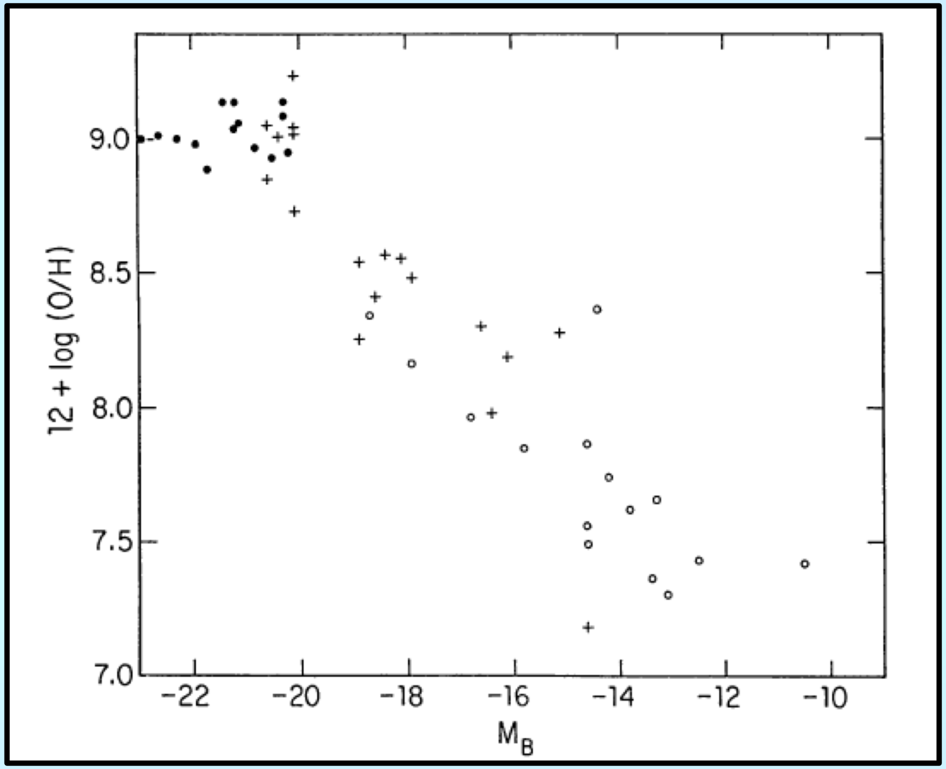
$$I(r) = I_0 \, e^{-r/r_0}$$

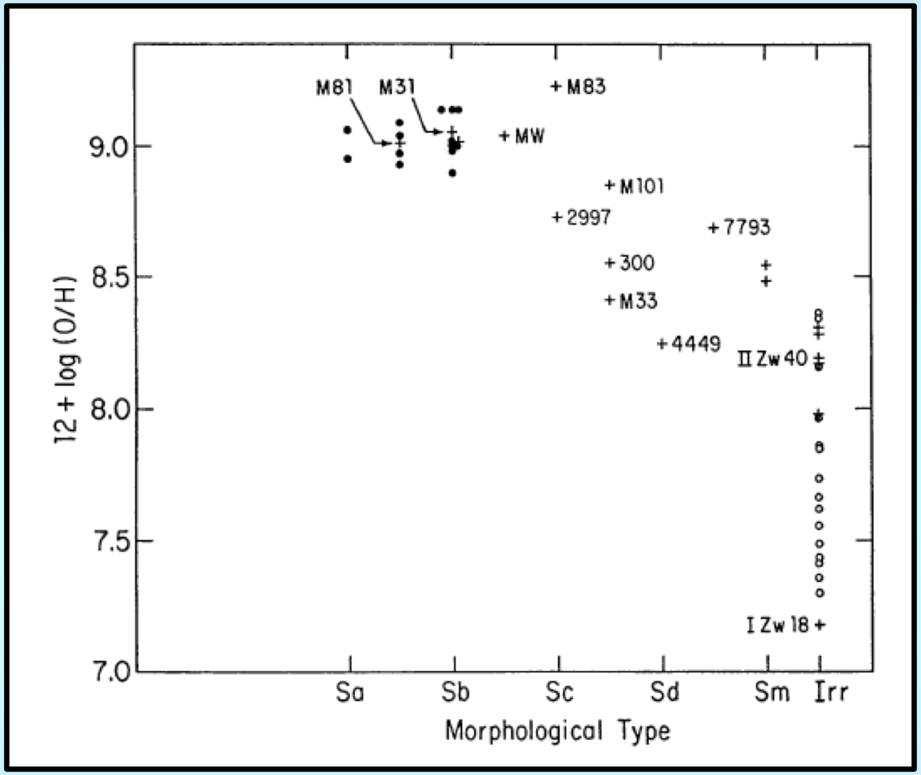
- I_0, central surface brightness, was at one time thought to be roughly constant for all spirals, but this is a selection effect.
- The vertical distribution of a spiral disk can be approximated as an exponential (or a hyperbolic secant)

$$\rho(z) = \rho_0 \, e^{-z/z_0} \quad \text{or} \quad \rho = \rho_0 \, \text{sech}^2\left(\frac{z}{2z_0}\right)$$

Spiral Galaxies

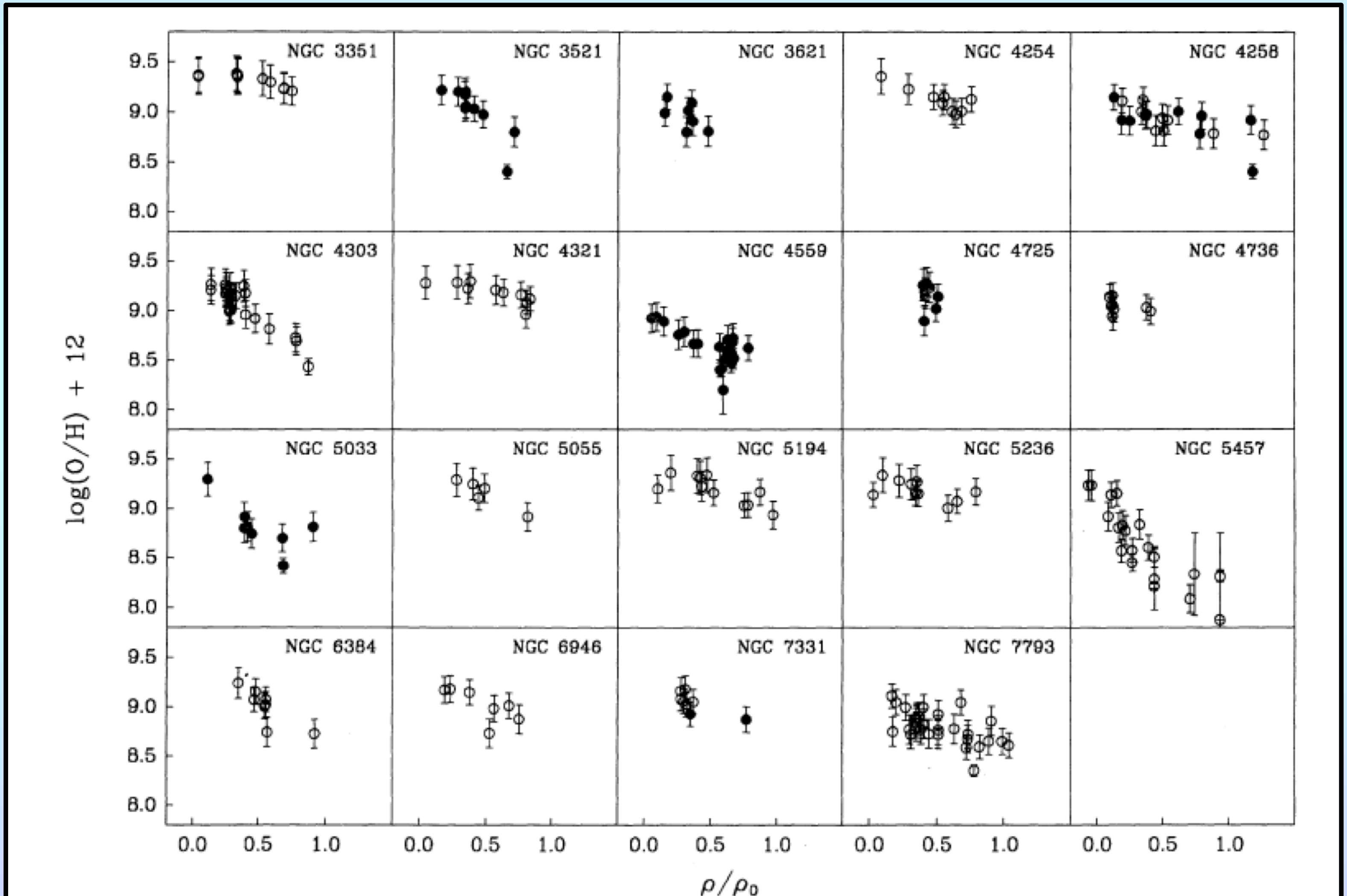
- Bright spirals are more metal-rich than faint spirals. Earlier-type (Sa) spirals are (probably) more metal-rich than later-type spirals.





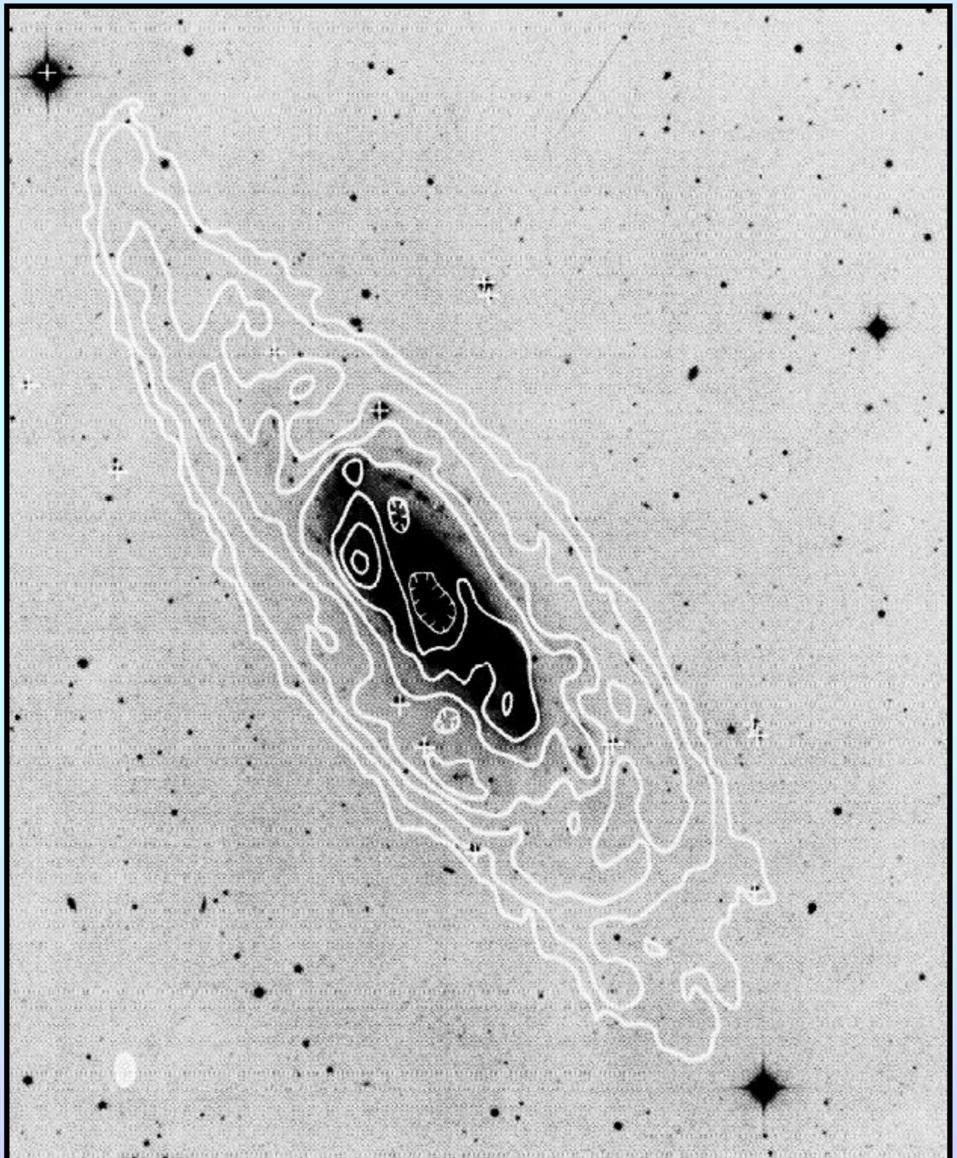
Spiral Galaxies

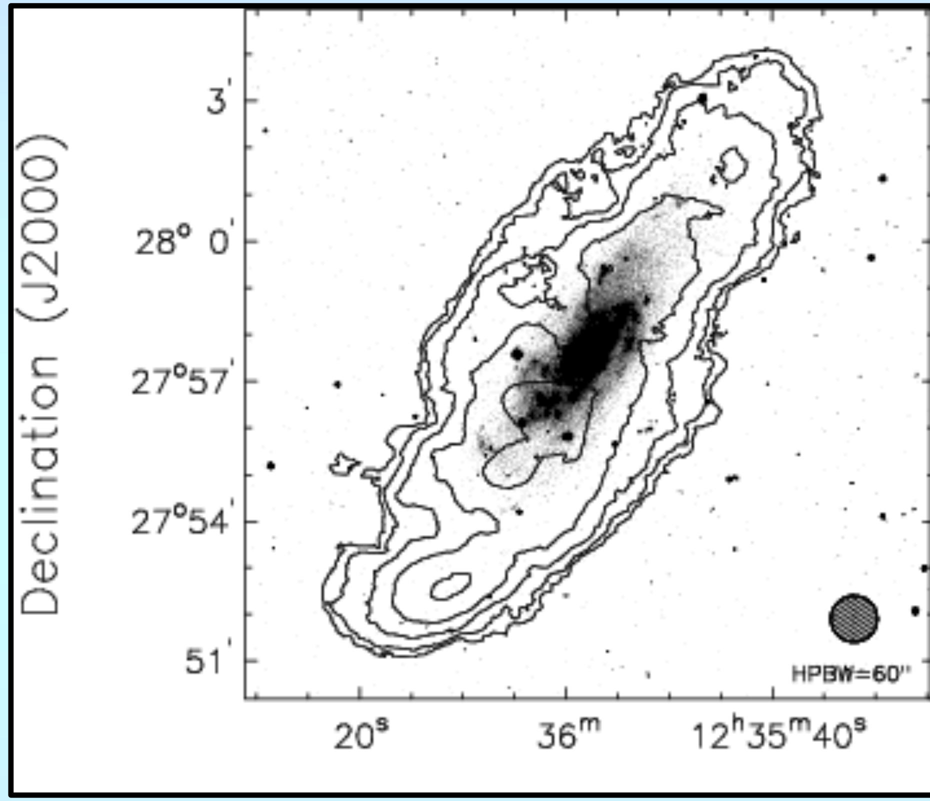
- The insides of spirals are more metal-rich than the outsides of spirals. (In other words, there is a metallicity gradient.)



Spiral Galaxies

- The gas of a spiral galaxy can extend far outside the optical disk.

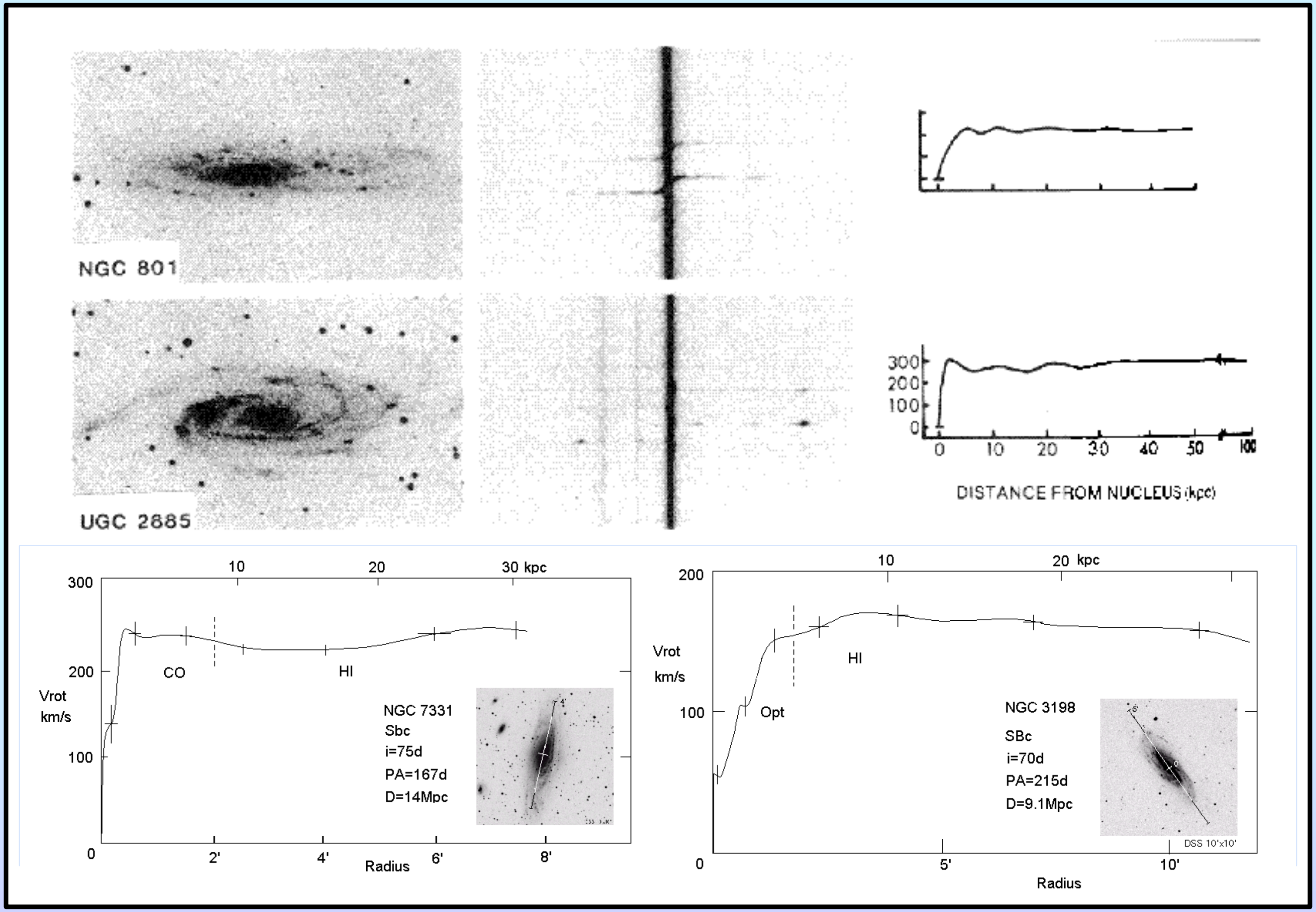




While most of the light has e-folded away, there are still trace particles of mass.

Spiral Galaxies

- The gas of a spiral galaxy rotates in a disk. For (just about) all spiral galaxies, the rotation speed (outside of the central regions) is independent of radius.



Spiral Galaxies

- The gas of a spiral galaxy rotates in a disk. For (just about) all spiral galaxies, the rotation speed (outside of the central regions) is independent of radius.
- Now, for circular orbits

$$\frac{mV^2}{r} = \frac{GM(r)m}{r^2} \quad \Rightarrow \quad M(r) = \frac{V^2 r}{G}$$

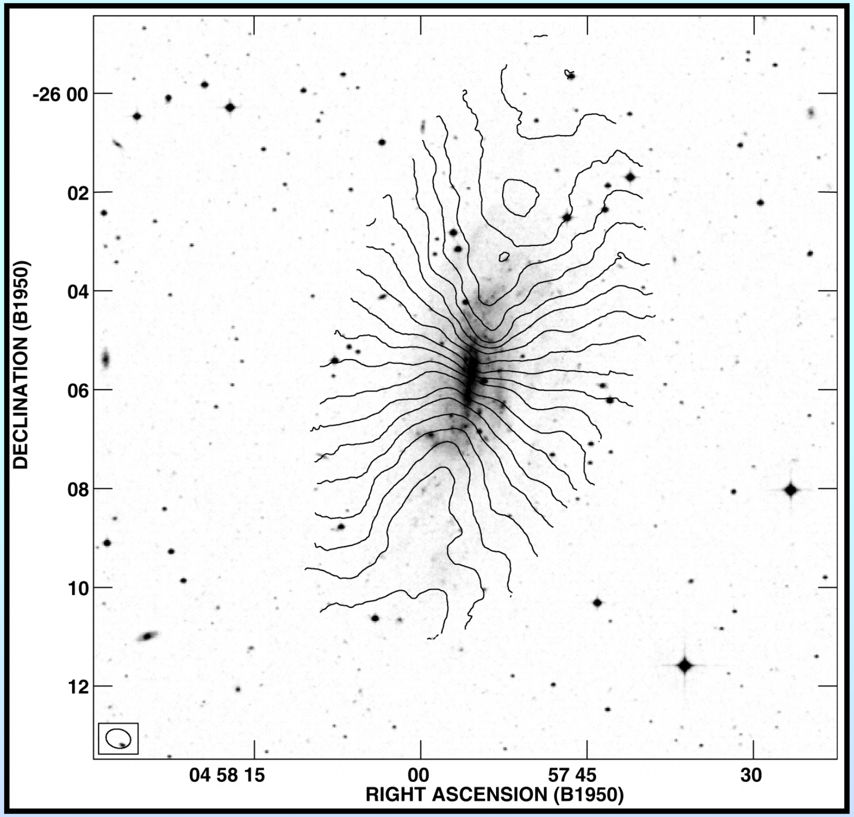
If there is no more mass in the galaxy, $V \propto r^{-\frac{1}{2}}$. On the other hand, if the rotation curve is flat, $M(r) \propto r$. So, in the case of a spherical galaxy

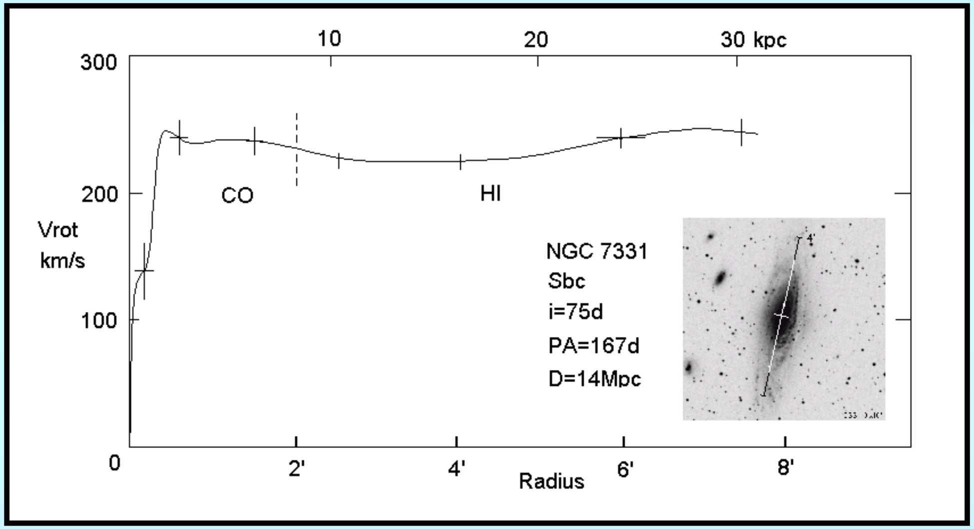
$$M(r) = \int 4\pi r^2 \rho(r)\, dr \quad \Rightarrow \quad \rho(r) \propto r^{-2}$$

This is the density distribution of an isothermal sphere.

Spiral Galaxies

- Spiral galaxies obey a luminosity-line width relation. If you take a spectrum of all the light of a spiral galaxy, the width of the H I 21-cm emission line (which reflects the rotation speed of the galaxy, corrected for inclination) is proprotional to luminosity.

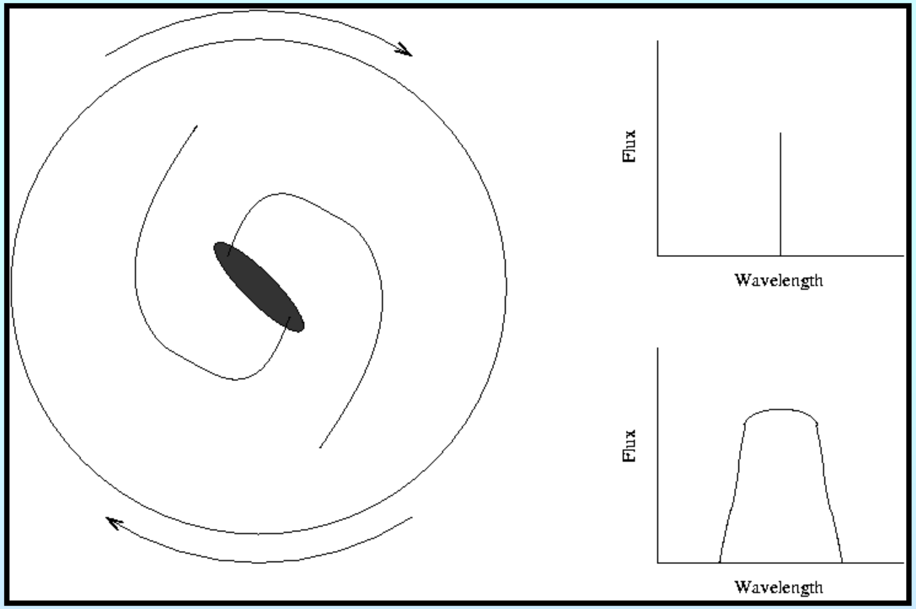




This is sometimes called the "Tully-Fisher Relation"

Spiral Galaxies

- Spiral galaxies obey a luminosity-line width relation. If you take a spectrum of all the light of a spiral galaxy, the width of the H I 21-cm emission line (which reflects the rotation speed of the galaxy, corrected for inclination) is proprotional to luminosity.



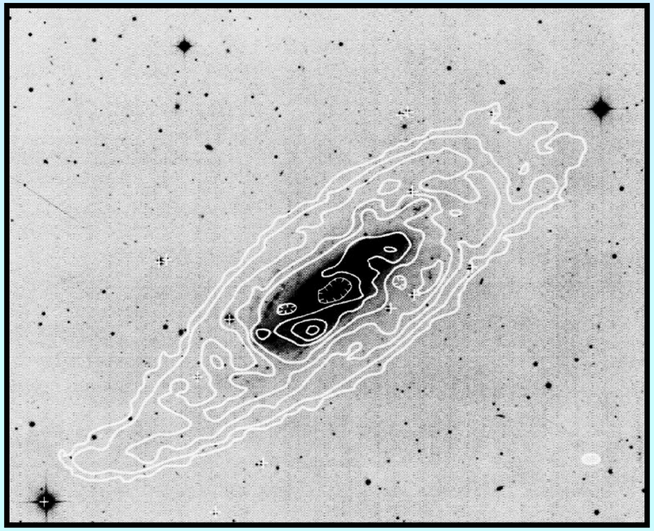
The true rotation velocity is

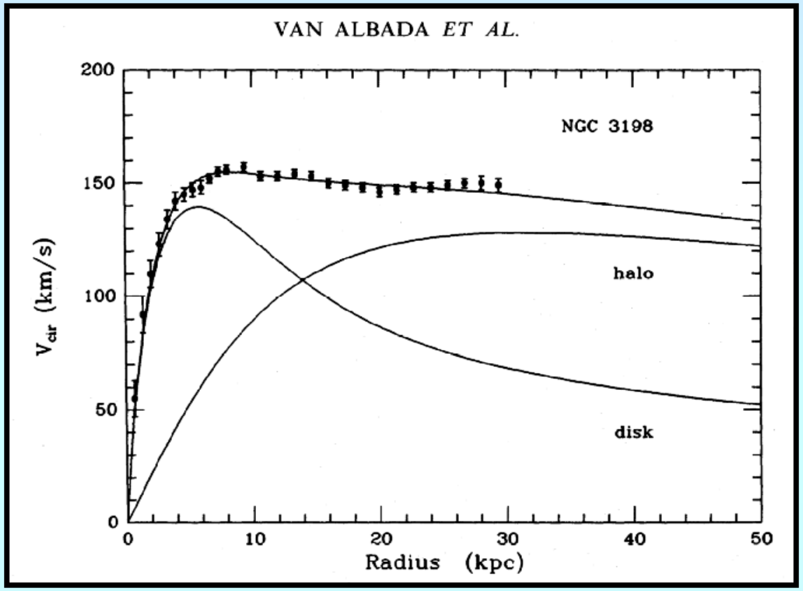
$$v_{rot}^2(r) \propto \frac{M(r)}{r}$$

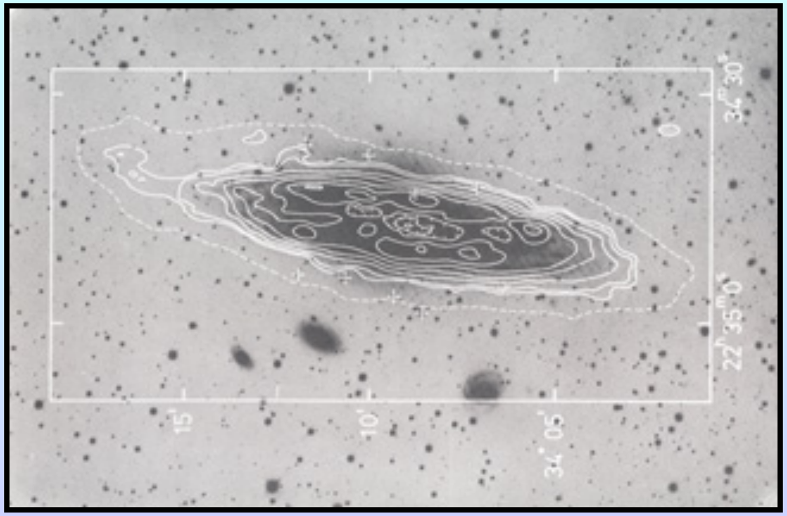
If we assume that the total mass of a spiral galaxy is related to its size, and the mass-to-light ratio of all spiral galaxies is the same, then $L \propto v^{\alpha}$. Since the observed Doppler width of an emission line is $W \propto v$, then in terms of magnitudes, $M = a \log W + b$

Spiral Galaxies

- If we assume that mass-to-light ratio of any point in the disk is constant, then we can model a spiral galaxy's rotation curve.







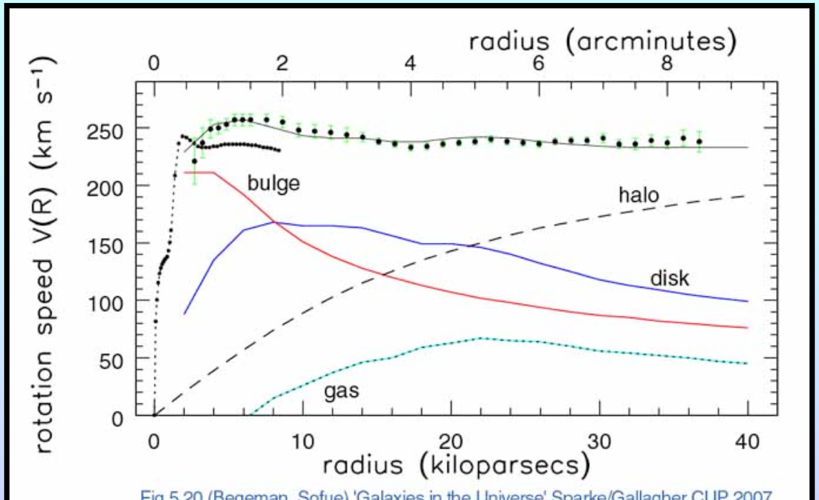


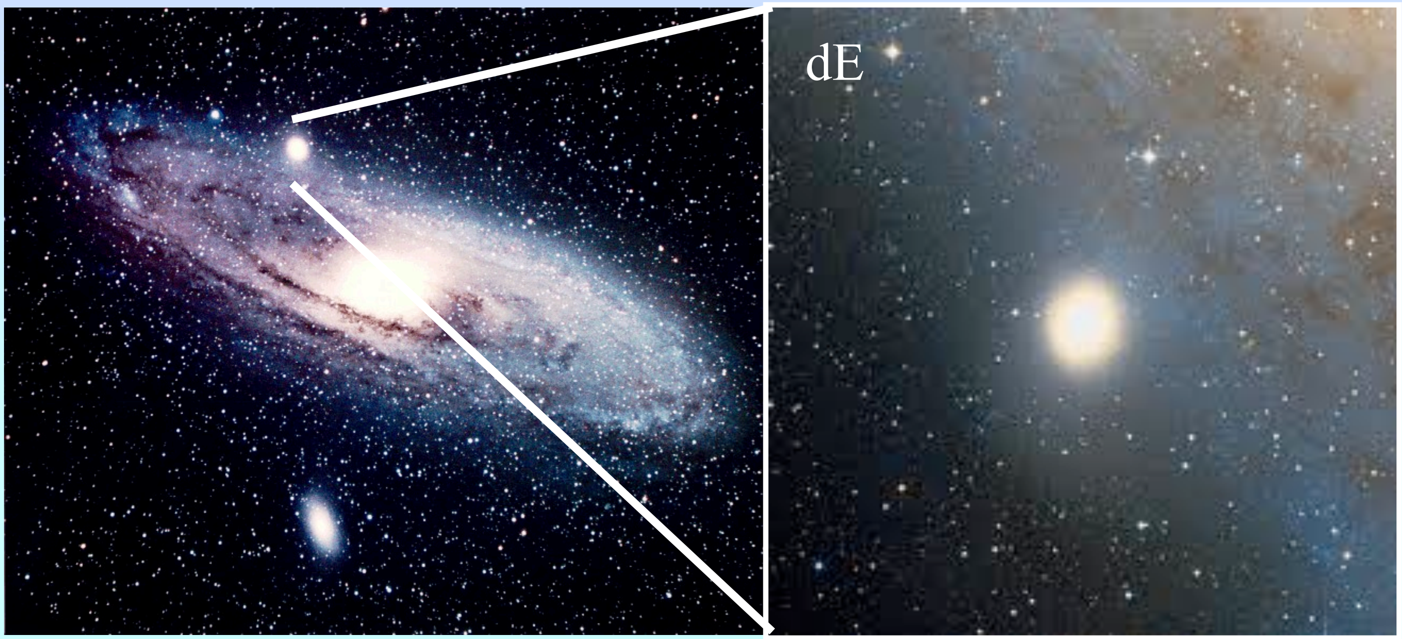
Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

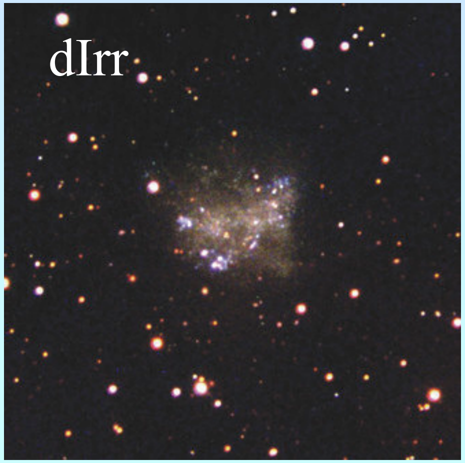
Dwarf Galaxies

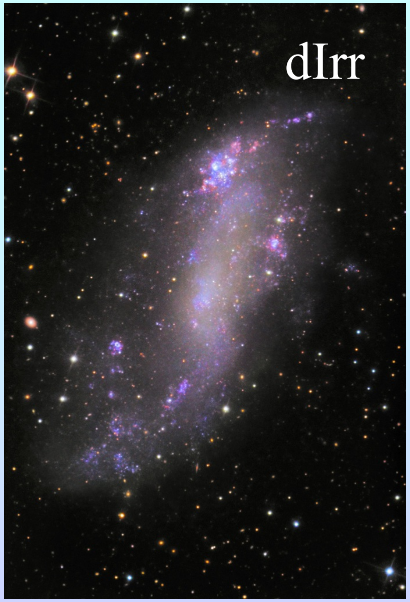
There are 3 basic types of dwarf galaxies:

- **Dwarf Ellipticals** are the low luminosity extension of normal giant elliptical galaxies; they obey the same relation as their larger counterparts.
- **Dwarf Spheroidals** are gas-poor, diffuse systems whose density profile is closer to an exponential disk than an $R^{1/4}$ law. These objects do not fall on the elliptical galaxy fundamental plane, and, in the Morgan classification scheme, would be given the letter "D" instead of "E".
- **Dwarf Irregulars** are low-luminosity extensions to spiral galaxies. In general, these objects are brighter than the dSph galaxies since they have active star formation, but if their star formation were to cease, they might evolve into a dSph.

Dwarf Galaxies

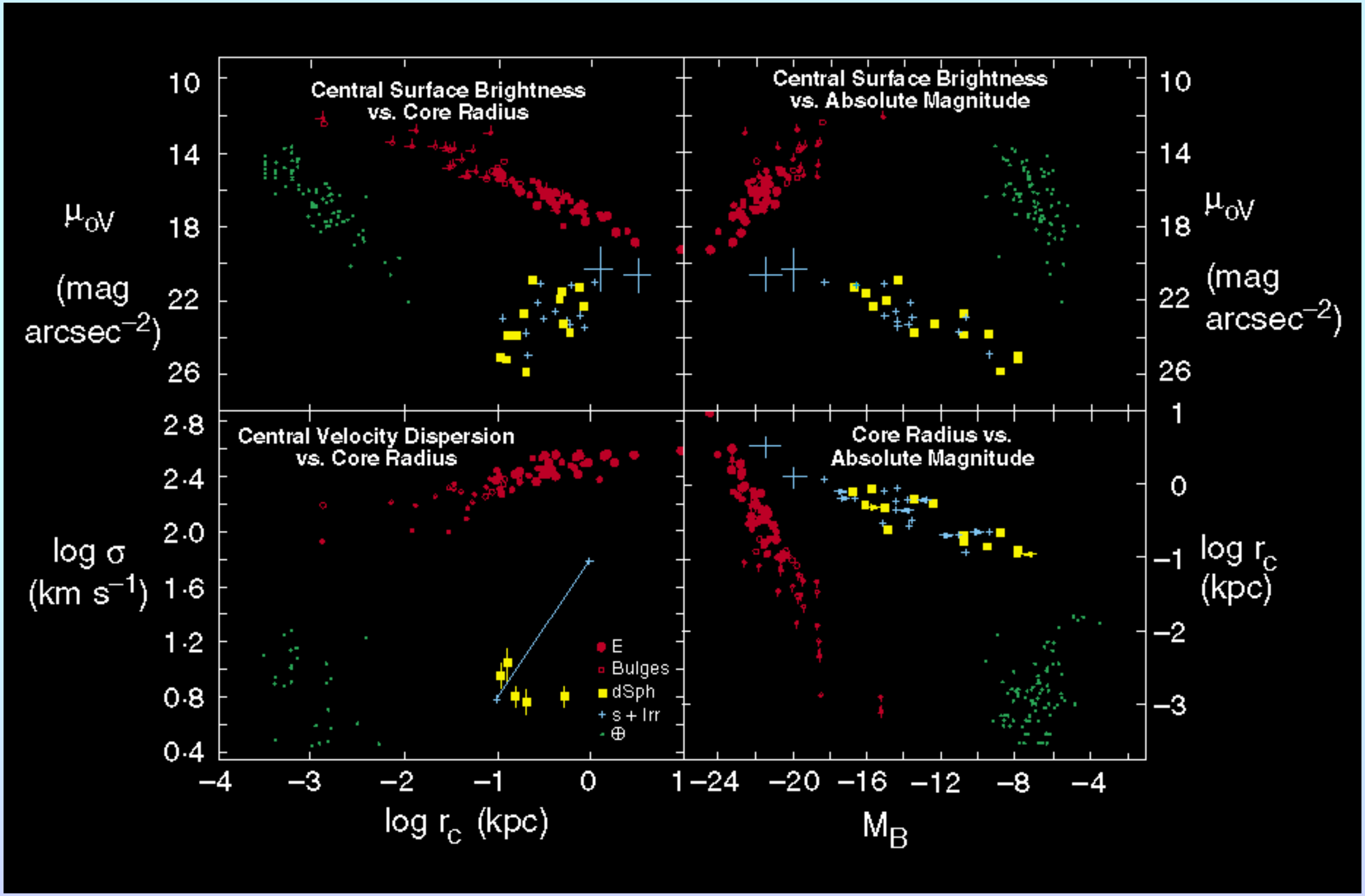






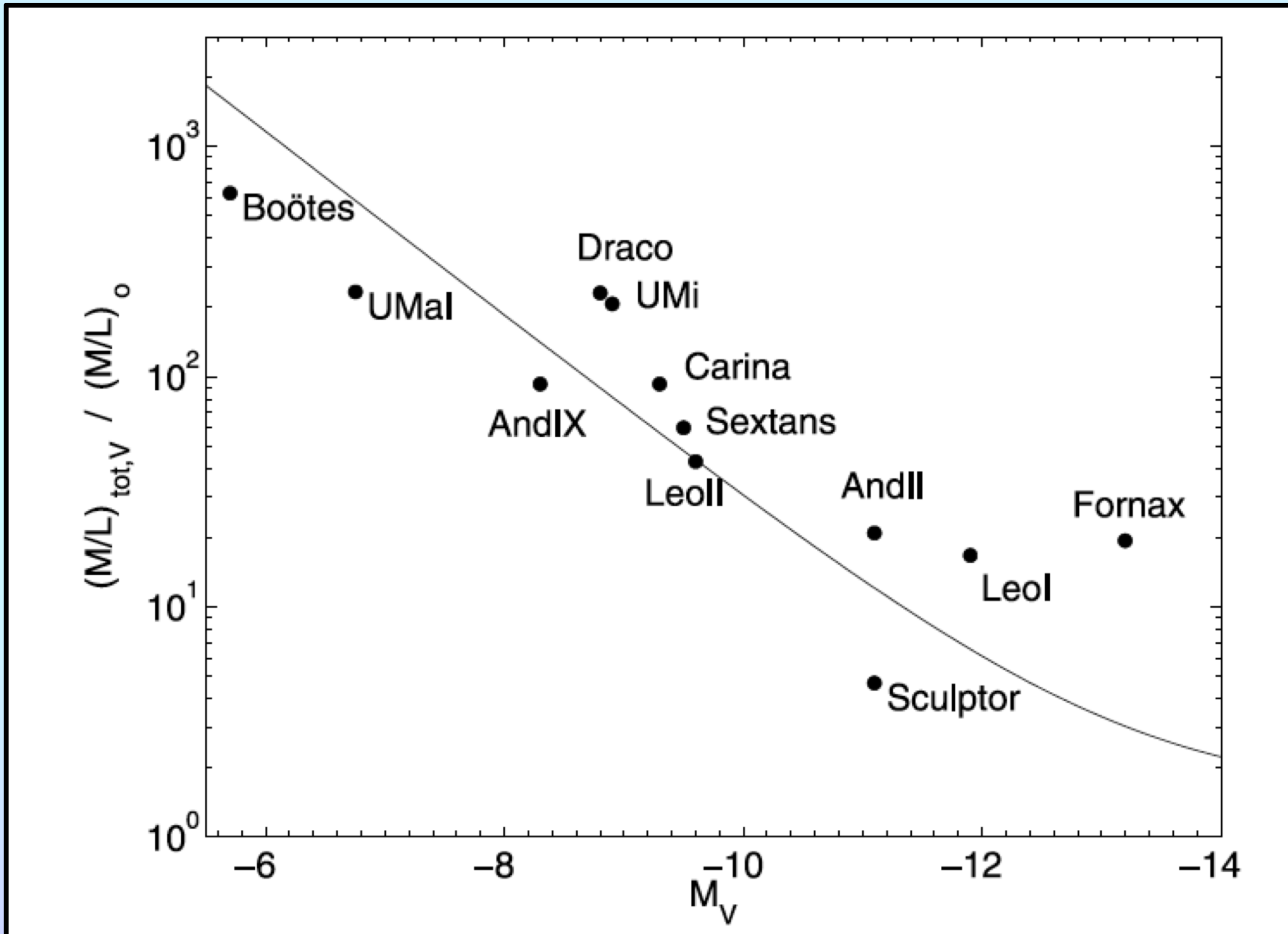
Dwarf Galaxies

Structurally and kinematically, dE and dSph galaxies are very different.



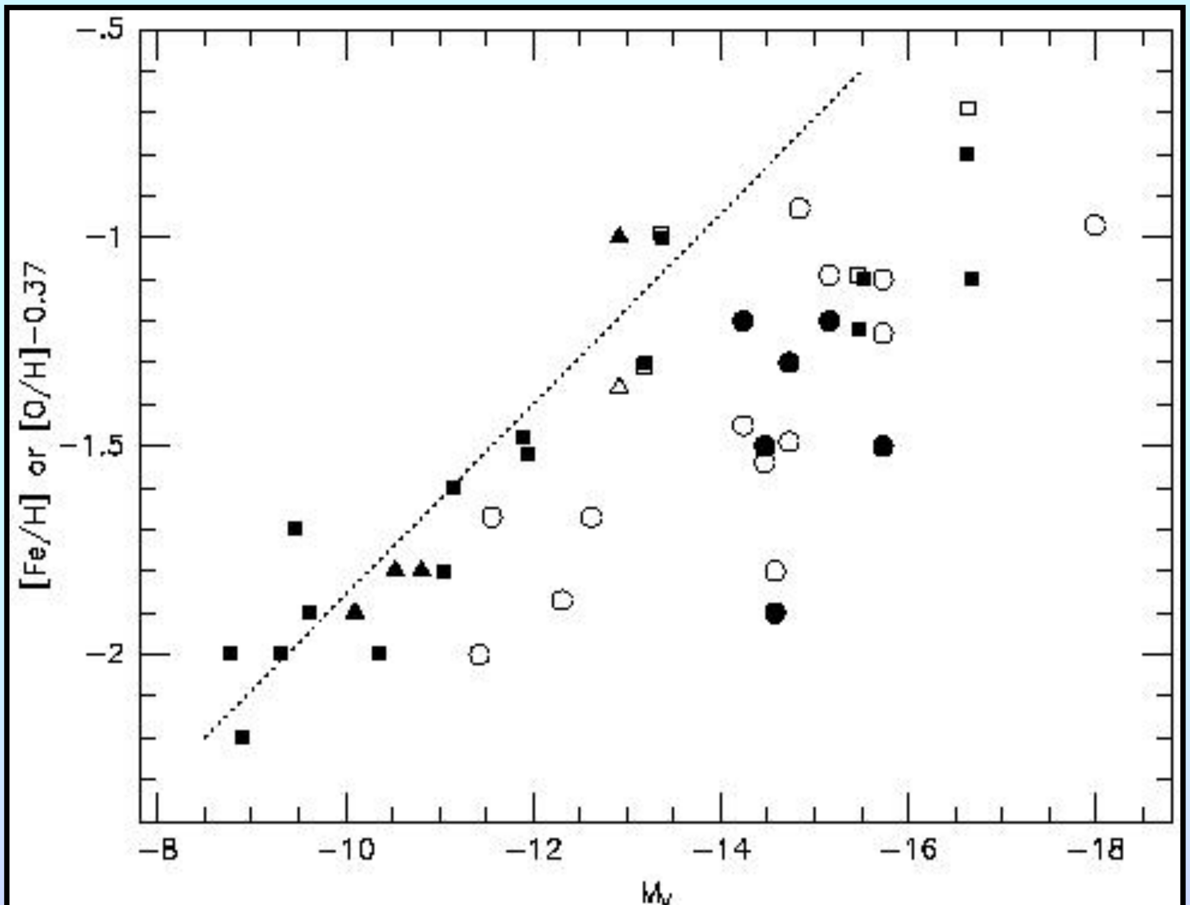
Dwarf Galaxies – Mass-to-Light

The mass-to-light ratio of dwarf galaxies can be extremely large. It appears that the fainter the galaxy, the greater its mass-to-light ratio.



Dwarf Galaxies -- Metallicities

Dwarf galaxies are typically very metal poor (but not as metal-poor as a Pop II globular cluster). This is consistent with the general mass-metallicity relationship that seems to hold for all galaxies.

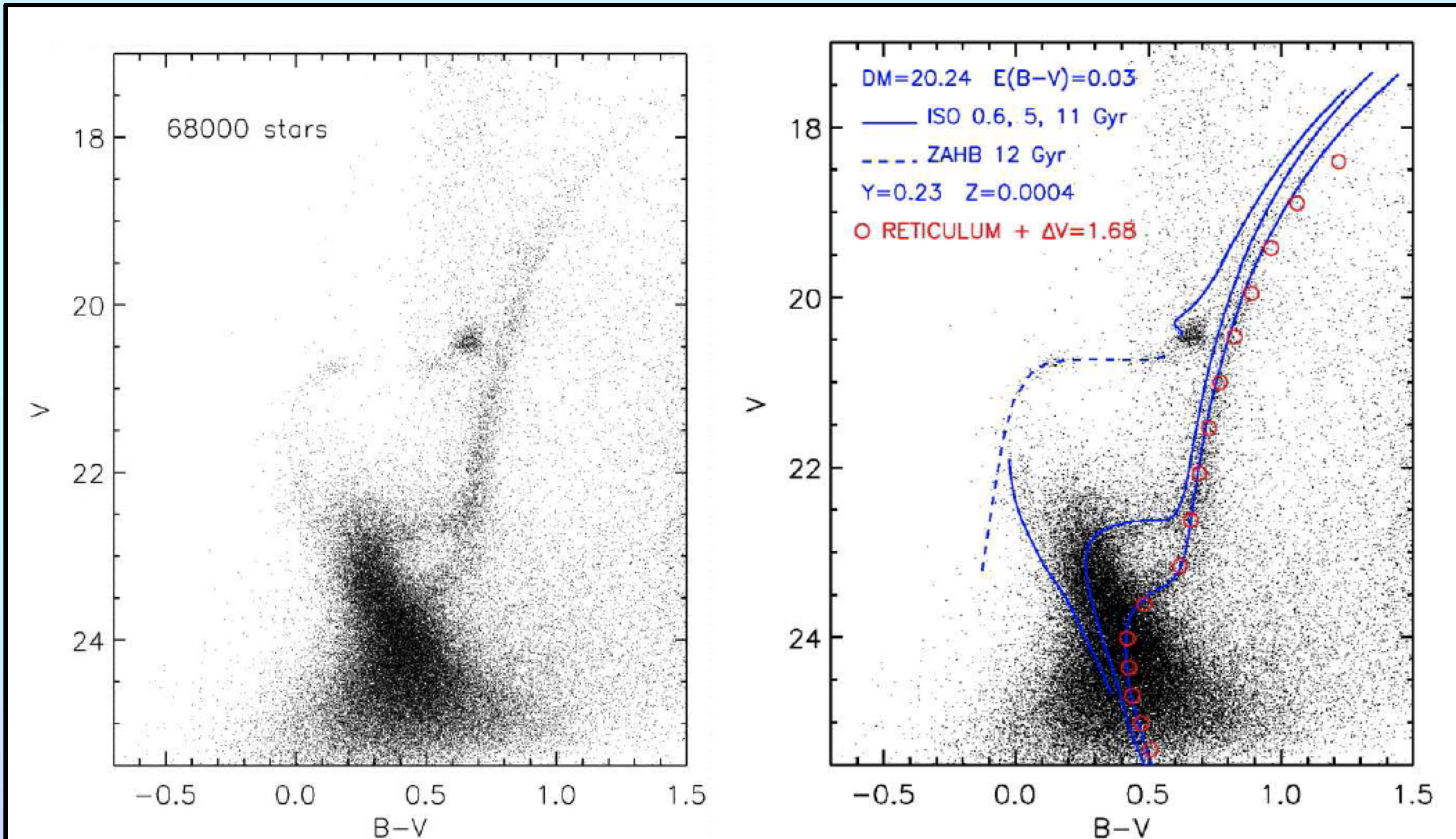


■ = dE or dSph
▲ = “transition”
● = dIrr

Filled = [Fe/H] of stars
Open = [O/H] – 0.37 of H II regions or PN

Dwarf Galaxies -- Populations

Dwarf galaxies may have more than one population. (This is a bit odd.)



Dwarf Galaxies -- Winds

Consider a galaxy of luminosity, L, and mass-to-light ratio, Υ. The stars in the galaxy are losing mass at the nominal rate of $\sim 10^{-11}\, M_\odot$ per year per solar luminosity of the population. Because the stars are moving randomly (and assuming minimal energy loss), the gas will thermalize at a temperature

$$\frac{GMm_H}{R} \sim \frac{G\Upsilon L m_H}{R} \sim \frac{1}{2} m_H v^2 \sim \frac{3}{2} k T_{\rm ISM} \implies T_{\rm ISM} = \frac{2}{3} \frac{m_H}{k} \frac{G\Upsilon L}{R}$$

Now assume supernovae occasionally go off in the galaxy. The supernovae ejecta travel at ~ 10,000 km/s. Let's suppose this matter thermalizes, perhaps at just $\varepsilon = 1\%$ efficiency.

$$\varepsilon \frac{1}{2} m_H v_{SN}^2 \sim \frac{3}{2} k T_{SN} \quad \Rightarrow \quad T_{SN} = \varepsilon \frac{1}{3} \frac{m_H}{k} v_{SN}^2$$

The temperature of the mixed material is then

$$T_{new} = \frac{\dot{M}_{ISM} T_{ISM} + \dot{M}_{SN} T_{SN}}{\dot{M}_{ISM} + \dot{M}_{SN}}$$

Dwarf Galaxies -- Winds

Now consider the system's escape velocity $v_{esc} = \sqrt{\dfrac{2GM}{R}}$. The characteristic temperature of this velocity

$$\frac{1}{2} m_H v_{esc}^2 = \frac{3}{2} k T_{esc} \implies T_{esc} = \frac{2}{3} \frac{m_H}{k} \frac{G \Upsilon L}{R}$$

So consider: when is the temperature of a mixed ISM greater than the escape temperature? After some simple algebra, $T_{new} > T_{ISM}$ when

$$L_{\rm wind} < \frac{\epsilon \, v_{SN}^2 \, R}{G \Upsilon} \frac{\dot{M}_{SN}}{\dot{M}_{ISM} + \dot{M}_{SN}}$$

For numbers, such as $\dot{M}_{ISM} \sim 10^{-11}\ M_\odot/\mathrm{yr}/L_\odot$, $\dot{M}_{SN} \sim 10^{-13}\ M_\odot/\mathrm{yr}/L_\odot$, $\varepsilon \sim 0.01$, $\Upsilon \sim 10$, and $R \sim 10$ kpc, $L_{wind} \sim 2 \times 10^9\ L_\odot$. Small galaxies cannot hold onto their interstellar medium. This makes having continuous star formation extremely difficult.